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SIMULATION MODELING OF THE EFFECTS OF OIL SPILLS ON
POPULATION DYNAMICS OF NORTHERN FUR SEALS

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PREFACE

The modeling work discussed in this report focuses on the potential long-term effects of oil spills on northern **fur** seal population dynamics. The model and analysis assume that specified numbers of fur seals have been oiled, even though the likelihood for such contact is very low. Based on resource estimates for past and proposed sales in the St. George Basin, the Minerals Management Service projects that about five oil spills of 1,000 barrels or greater would occur over the life of the field. We project that the probability of a 10,000 barrel oil spill occurring and striking the **Pribilofs** is less than two chances out of 100 (0.02); the probability of two such events is therefore less than four chances out of 10,000 (0.0004), assuming independence between events. Two hypothetical spills of 10,000 barrels of oil are simulated in this report, and are precalculated to occur at times and places which result in substantial fur seal mortality due to oil contact.

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ABSTRACT

Population dynamics and migration models were developed and combined with an oil spill simulation **model** to determine the effects of oil spills on the **Pribilof** Island fur seal (*Callorhinus ursinus*) population. In the population dynamics model, mortality of pups on land and juveniles up to two years of age is density dependent, while that of older seals is **age-** and sex-specific and constant at all population sizes. **Movement** patterns of seals within the Bering Sea are functions of date, sexual status and age, conforming to probability distributions based on field observations of their movements and timing.

Two hypothetical 10,000 barrel oil spill simulations were performed. One occurs near Unimak Pass during the peak migration of pregnant females to the **Pribilof** rookeries, oiling 3% of the total female population. The other occurs near St. Paul Island during the pupping season, and oils 2-4% of the female population. By comparison, about 16% of females die from natural causes each year. Depending on the assumed oil-induced mortality rate in the range 25%-100%, "effective" recovery of the population from these spills, i.e. the number of years **before** the oil-affected population numbers were within 1% of the non-affected population numbers, took 0 to 25 years.

Executive Summary

A population dynamics model with spatial resolution was developed to determine possible long-term effects of oil spills on the Pribilof Islands fur seal herd. A comprehensive literature review was conducted both of previous pinniped models and all aspects of fur seal behavior and population dynamics. In addition the pelagic fur seal data base of over 4000 collected animals was analyzed for a variety of distribution data. A conceptual framework for the model was constructed and refined in a workshop of fur seal investigators. From this framework, a numerical model was coded and tested to reflect data on population dynamics of fur seals and to simulate population dynamics and movement patterns of seals in the Bering Sea. This fur seal model has been linked to an oil spill trajectory and weathering model to produce estimates of effects of oil spills on the population.

Two hypothetical 10,000 barrel spill simulations were performed. The first was near Unimak Pass while the seals were entering the Bering Sea from the Gulf of Alaska in spring; the second was near the southern coast of St. Paul Island in the middle of July, when maximum numbers of seals were assumed present at the rookeries. Because these spill simulations were selected to occur at times and places which result in substantial fur seal mortality, they may be considered "extreme cases" for spills of their size, with low probabilities of occurrence.

Based on the 1986 population, estimated at 739,000 seals, the Unimak Pass spill resulted in a mean of about 14,000 seals encountering oil. Stochastic model components resulted in a standard deviation about the mean of about 1400. Depending on whether oil-induced mortality was assumed to be 25%, 50%, 75%, or 100%, modeled differences in numbers between affected and non-affected populations ranged from about 16,000 to nearly 24,000. Due to the timing and location of this hypothetical spill, most of the seals affected (13,000 or 91%) were females. Each pregnant female dying due to effects of the oil also resulted in the loss of her pup, explaining why total resultant differences exceeded the number of seals actually encountering oil.

The simulated St. Paul oil spill resulted in a mean number of 17,000 or 31,000 seals from the estimated 1986 population encountering oil, depending on whether seals on the rookeries were assumed to stay on land and avoid nearshore oil, or whether they were assumed to enter the water at least once a day whether oil was present or not. In either case, 59% of the seals oiled were females. Including stochastic variability in the model and a range of oil-induced mortality rates (i.e. 25% to 100%), the differences in numbers between oil-affected and non-affected populations varied from about 6,000 to 42,000 at the end of the year.

The percentage of the equilibrium population which dies from natural causes each year is 16% for females and 29% for males. For the 1986 population with an added mortality factor, perhaps due to entanglement in

net fragments (**Fowler** 1984, 1985), mortality due to natural causes plus entanglement is 18% of the females and 32% of the males over 1 year. In comparison, the "extreme case" spill simulations herein would be expected to oil and kill at most **4%** of the population. Since the **number** of seals **oiled** by a given oil spill simulation is approximately proportional to population size, these percentages would be similar at other population sizes, assuming a similar age and sex structure.

The recovery time of the fur seal population following perturbations due to hypothetical **oil spills** was of particular interest in this study. We defined recovery time as the time from the initial perturbation until the difference between oil-affected and non-affected populations became less than a specified percentage of the non-affected population 'size. We have used both 0.1% and **1%** as measures of recovery, noting that 1% is near the level of accuracy for pup counts on the rookeries and, therefore, is a measure of "effective" recovery time. Recovery can be considered "complete" at the 0.1% level. The time for complete recovery for the maximum oil-affected case was about 60 years. At the 1% level, which more closely reflects our ability to **observationally** discern population differences, the maximum recovery time **was** about 25 years. For the **smallest** case simulated here, in which about 5,700 seals were killed, less than 1% of the population was lost, a perturbation which would not be measurable in the field.

The number of seals oiled by a spill will vary considerably with spill size, location and timing, and may vary with such model parameters as the number of discrete patches of oil, the shape of oil slicks, the swimming velocities of seals and the number of feeding areas individual seals visit. Therefore, it would be desirable to conduct further sensitivity analyses on the fur seal migration - oil spill interaction component of the **model**. The results, **combined** with probability estimates for individual spill events, would generate a relationship between the number of seals oiled and the probability of such an **occurrence** (Figure 1). In addition, oil behavior in the near-shore zone could be more explicitly modeled by incorporating the coastal zone oil spill model now under development for **MMS** (**Gundlach** et al, 1986).

The population dynamics model **may** be applied to other problems concerning the **Pribilof** Island fur seal population, such as the importance of lethal entanglement and other potential causes of the **population** decline since 1958. The significance of changes in entanglement rate and resulting mortality may be explored. Finally, the migration model, in conjunction with the population dynamics model (or estimates of population sex and age structure), can provide estimates of fur seal densities in time and space for applications in addition to interactions with oil spill simulations,

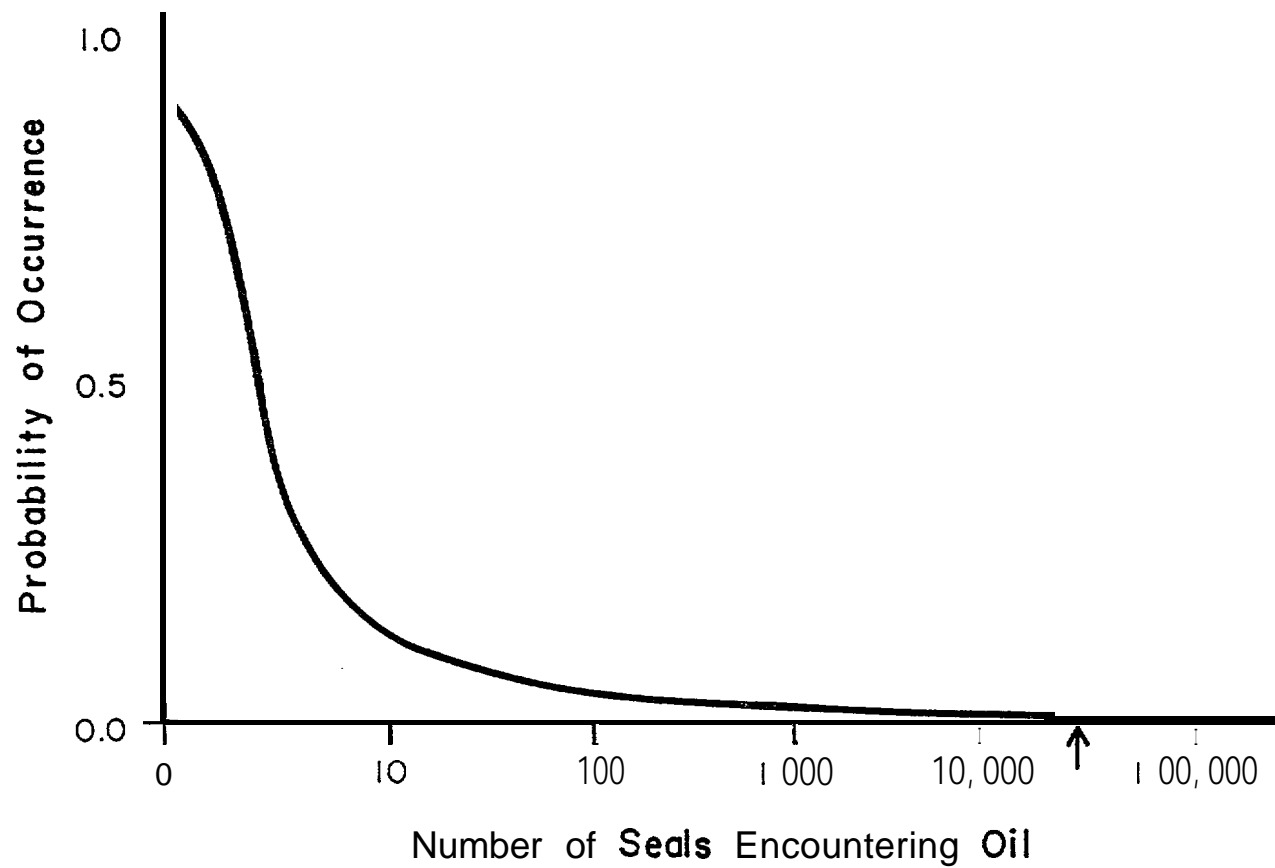


Figure 1. Conceptual probability distribution of oil spill events versus number of fur seals encountering oil.*The arrow indicates the location on the curve of the oil spill simulations reported here.

1. Introduction

The Department of the Interior has delegated to the Minerals Management **Service** most of the responsibilities on matters relevant to **mineral** resource development on the Outer Continental Shelf, subject to protection of the marine and coastal environment. Certain species of marine mammals which may be in danger of depletion or extinction represent special areas of concern to the MMS. The northern fur seal (*Callorhinus ursinus*), for which the majority of the population breeds on the **Pribilof** Islands in the **Bering** Sea (Figure 1-1) appears to be declining in numbers (Fowler, 1985a). Therefore, the **northern** fur seal population may be unusually susceptible to perturbations such as might be associated with oil spills.

The purpose of this study was to estimate potential long term effects of oil **spills** on the **Pribilof** Island fur seal population. A three stage methodology has been used to achieve this purpose:

- (1) review of literature on pinniped models and northern fur seal biology;
- (2) conceptual formulation of population dynamics and migration models with the capabilities necessary for estimation of oil spill effects;
- (3) coding, testing, and application of the model system to produce estimates of long term effects,

Results of the literature review are summarized in Section 2, with details given in the Appendix. Following completion of the review, a preliminary conceptual outline was created for a fur **seal** population dynamics model which could be coupled to an oil spill model. This proposed model was then presented, reviewed, and amended at a meeting held **at** the National Marine Mammals Laboratory on February 28, 1985, in Seattle, Washington. Participants other than the authors of this report are listed in the acknowledgements. An overview of the fur seal model components (population dynamics and migration) is **described** in **Section 3**, with details of the model and implementation given in Section 4.

The oil spill model used in the study, and the linkages to the fur seal population dynamics model, are described in Section 5. Model system sensitivity studies and simulation results **are then** discussed **in** Sections 6 and 7, respectively.

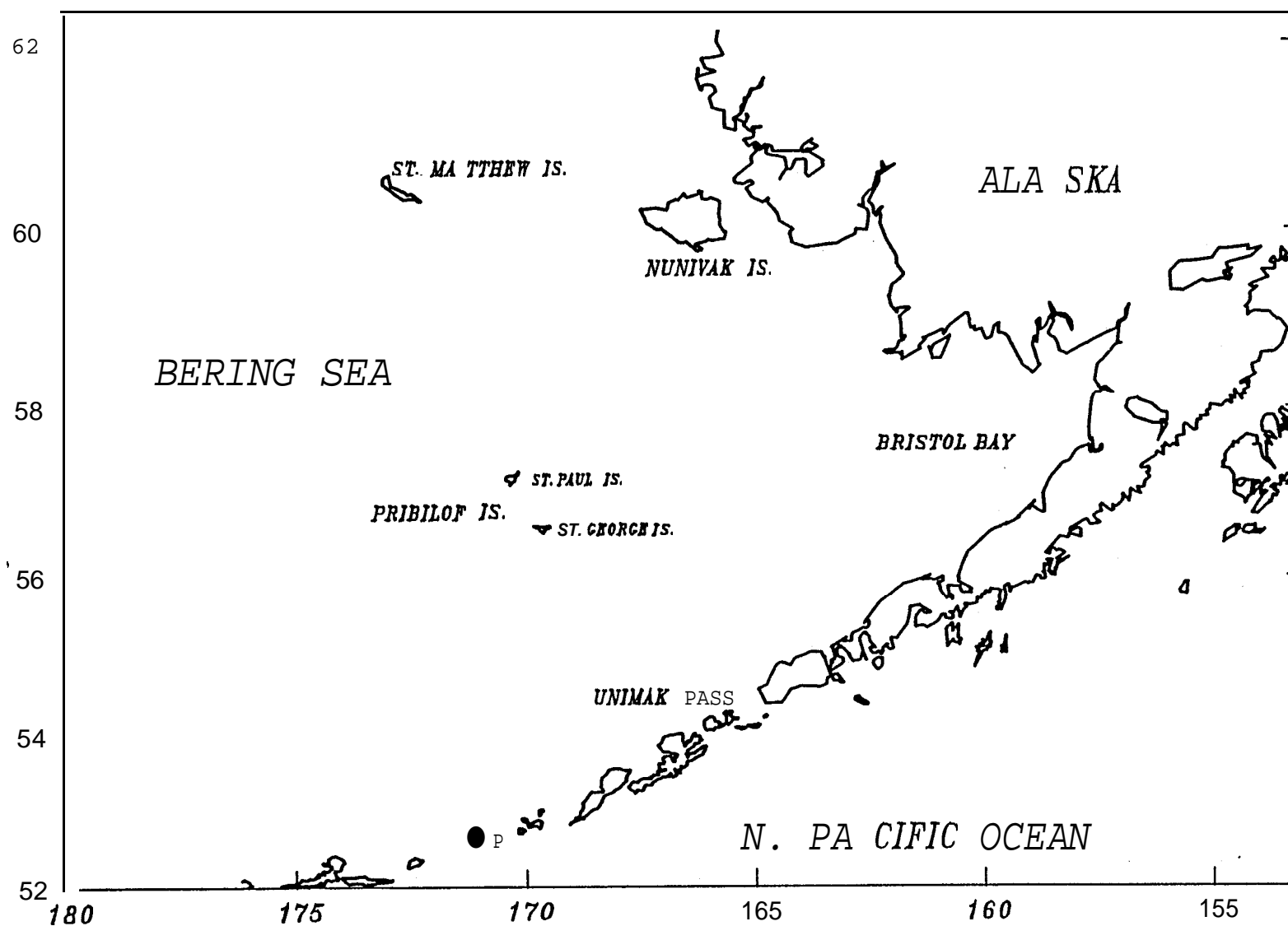


Figure 1-1. Study area map of the Southern Bering Sea.

2. Summary Literature Review

Literature reviews of **northern** fur seal research on biology, physiology, population dynamics, and migrational patterns were performed. The **most** current literature is summarized in the following **section**. Section 2.2 gives an overview of the background literature on pinniped population models.

2.1 Northern Fur Seal Literature

The body of research on northern fur seals is extensive, exceeding the volume for any other marine mammal. Table 1 in the Appendix summarizes recent literature relevant to construction of a population model capable of evaluating the effects of an oil spill in the Bering Sea.

Most older reports have been superseded by recent research that more accurately reflects the current status of the fur seal herd. Many of the data required for population modeling are derived from extensive pelagic collections conducted by the governments of Canada and the United States between 1958 and 1974 (**Kajimura** et al. 1979, 1980a, 1980b). Reproductive parameters such as age at first reproduction and age-specific reproductive rates are best summarized in Lander (1980a; 1981), and York (1980a, 1983). Pup production estimates are relied on as the primary method of determining trends adult females and the overall population and are included in annual fur seal investigators' reports published by NOAA. Pup production figures combined with mortality rates formed the basis for Lander's (1980a) life table on northern fur seals.

The northern fur seal **population** on the **Pribilofs** has declined substantially in recent years (1960's - present). Part of the cause for this decline appears to be the herd reduction of nearly 300,000 females **harvested** on St. George and St. Paul from 1956 to 1968 originally conducted to increase productivity (York and Hartley, 1981). The factors responsible for the continued contemporary decline have not been determined; a plausible hypothesis is lethal entanglement of a large number of animals in discarded fishing nets which increased in rate after 1965 due to changes in gear and fishing effort (**Fowler**, 1982; 1985a;b; 1985; **Swartzman**, 1984).

Some density dependent factors have been described in fur seals. Eberhardt and Siniff (1977) suggest that survival through juvenile stages is the **most** critical density dependent parameter. Density dependent factors in fur seals appear to act at high population levels near the population carrying capacity (**Fowler**, 1981; **Eberhardt** and Siniff, 1977). How density dependence is reflected in population dynamics at depressed population levels remains uncertain.

Migration and seasonal distribution of fur seals are critical factors for evaluating the effect of an oil spill on the population. Fur seal distribution by age and sex is summarized in Bigg (1982) and Kajimura (1980). This information has been integrated with data on onshore-offshore movements and interchange of different sex and age groups determined from behavioral research (Gentry 1981, Gentry and Holt 1985, Gribben 1979, Peterson 1968) in the development of the migration model.

Feeding habit studies derived from years of pelagic seal collection indicate fur seals are opportunistic feeders preying on a wide variety of fish and cephalopods (Kajimura 1984, Perez 1979). The prey of fur seals includes species that are commercially harvested. However, food does **not** appear to be a limiting factor for northern fur seals (Fowler 1982, 1985a, Swartzman 1984).

2.2 Pinniped Population Models

A total of 21 literature sources were identified in which pinniped (seal or walrus) models are described (Table 2-1).

Table 2-1. Pinniped Population Models Identified in the Literature

<u>Authors</u>	<u>Pinniped Population</u>
Allen, 1975	NW Atlantic Harp Seal
Bulgakova , 1971	Russian fur seal
Capstick , et al 1976	NW Atlantic harp seal
Capstick and Ronald, 1982	NW Atlantic harp seal
Chapman, 1961	Alaska fur seal
Chapman, 1973	Alaska fur seal
DeMaster, 1981	Alaska fur seal
Eberhardt and Siniff , 1977	Alaska fur seal
Eberhardt, 1981	Alaska fur seal
Flipse and Vellig , 1984	NE Atlantic hooded seal
Frisman , et al 1982	Tyuleniy Island fur seal
Harwood, 1981	British gray seal
Lett and Benjaminson , 1977	NW Atlantic harp seal
Lett , et al 1981	NW Atlantic harp seal
Nagasaki, 1961	Northern fur seal
Shaughnessy and Best, 1982	South African fur seal
Siniff , et al 1977	Antarctic Weddell seal
Smith and Polacheck , 1980	Alaska fur seal
Swartzman , et al 1982	Alaska fur seal
Swartzman , 1984a	Alaska fur seal
Trites , 1984	Alaska fur seal
York and Hartley, 1981	Alaska fur seal

A large number of quantitative studies, such as the life table studies by Lander (1980a), or the entanglement mortality work by Fowler (1982), are extremely important for the understanding of population biology and for the development of information bases upon which future modeling studies depend, but they are not population models per se, and have not been included here.

Reviews of the 21 models are summarized in Table 2, in the Appendix. Of these models, at least 11 are based on some variant of the Leslie (1945) matrix approach. The remainder cover a range from simple, single equation models relating surviving pups to adult population size ("spawn-recruit") models, to relatively complex models relating survival explicitly to food availability and seal energetic. Population models without density dependent mechanisms are generally unstable to perturbations in parameters; only the models by Allen (1975) and Trites (1984) do not contain some density dependent survival or reproduction mechanism. In all cases for which some sensitivity analysis was performed, density dependent parameters appear at the top of the sensitivity hierarchy.

In modeling the effect of potential oil spills on the Pribilof fur seal population, it may be important to consider processes such as feeding, migration, and physiological energy balances for animals of both sexes and at various stages of sexual development. A standard female-based year-class Leslie matrix formulation is therefore insufficient. Models which contributed most towards the conceptualization of the model for this project are Frisman et al (1982), Lett et al (1981) and Swartzman et al (1982). The work by Frisman et al addresses a variety of age and sex groups. The model by Lett et al, based on Lett and Benjaminson (1977), includes both males and females, and simulates natural mortality as a normally distributed stochastic process. Swartzman et al (1982) is of special interest because of the focus on explicit predation relationships and seal energetic.

None of the models reviewed addresses spatial distribution of pinnipeds. The work of Swartzman et al (1982) represents a marginal exception, in that seals are either on or away from the Pribilofs depending on time of year. Explicit spatial distribution is a crucial factor in coupling a fur seal model with an oil spill model for effect assessment purposes. This fur seal model is therefore a departure from all previous models, although the collected experience of previous biological and modeling work provides a valuable basis for model genesis.

3. Fur Seal Model Overview

This report section defines the conceptual basis for the numerical model to assess the effects of potential oil spills on the fur seal population in the **Pribilof** Islands - Southern **Bering** Sea region. Details of formulations and literature sources for parameters are given in Section 4. The physical distribution aspects of the proposed model focus on the geographic area north of the Aleutian Islands, although the northern fur seal migratory domain extends southward to the California coast. Other limitations on the model are primarily those enforced by the limits of our knowledge about northern fur seals themselves and the ecosystem within which they exist.

A schematic of the fur seal - oil spill model system is shown in Figure 3-1. The oil spill trajectory and spreading-weathering model (top circle) is a separate entity which supplies time series information to the population and migration model (**lower circle**). The linkage between the two models is accomplished through dynamic comparison of oil and seal spatial distributions, and application of an oil-induced mortality algorithm within the population dynamics model.

The fur seal population model addresses the dynamics of specific groups of seals, differentiated by sex, sexual status, and age, as they feed, reproduce and migrate in space and time. Individual points are used to track seal locations. Because computational time (and costs) increase approximately exponentially with the number of points used to represent the population, each point represents a number of seals of like characteristics. The number of points used to represent the population is large enough such that the modeled distribution is not significantly different from observations made in the wild. The status of a seal group (point) is defined by the following parameters: age (in days), sex, reproductive status (**immature**, mature, pregnant, lactating, territory-holding, non-breeding), on land or at sea, oiled or not oiled. Associated with each seal particle is a location (latitude and longitude), and seals move in accordance with a time-dependent migration model and feeding cycles within the Bering Sea, which are dependent on age, sexual and **breeding status**. When seals are outside the Bering Sea, their spatial dynamics are not specifically simulated, while population dynamics (fecundity and mortality) are modeled for the entire annual cycle.

3.1 Population Dynamics

A schematic of the fur seal population model is shown in Figure 3-2. Pups born in June and July remain associated with the appropriate mother seals and nurse on land until weaning in **November**. Mortality of pups is density dependent, in that **mortality** on land increases with increasing number of pups born. In addition, if a lactating seal dies due

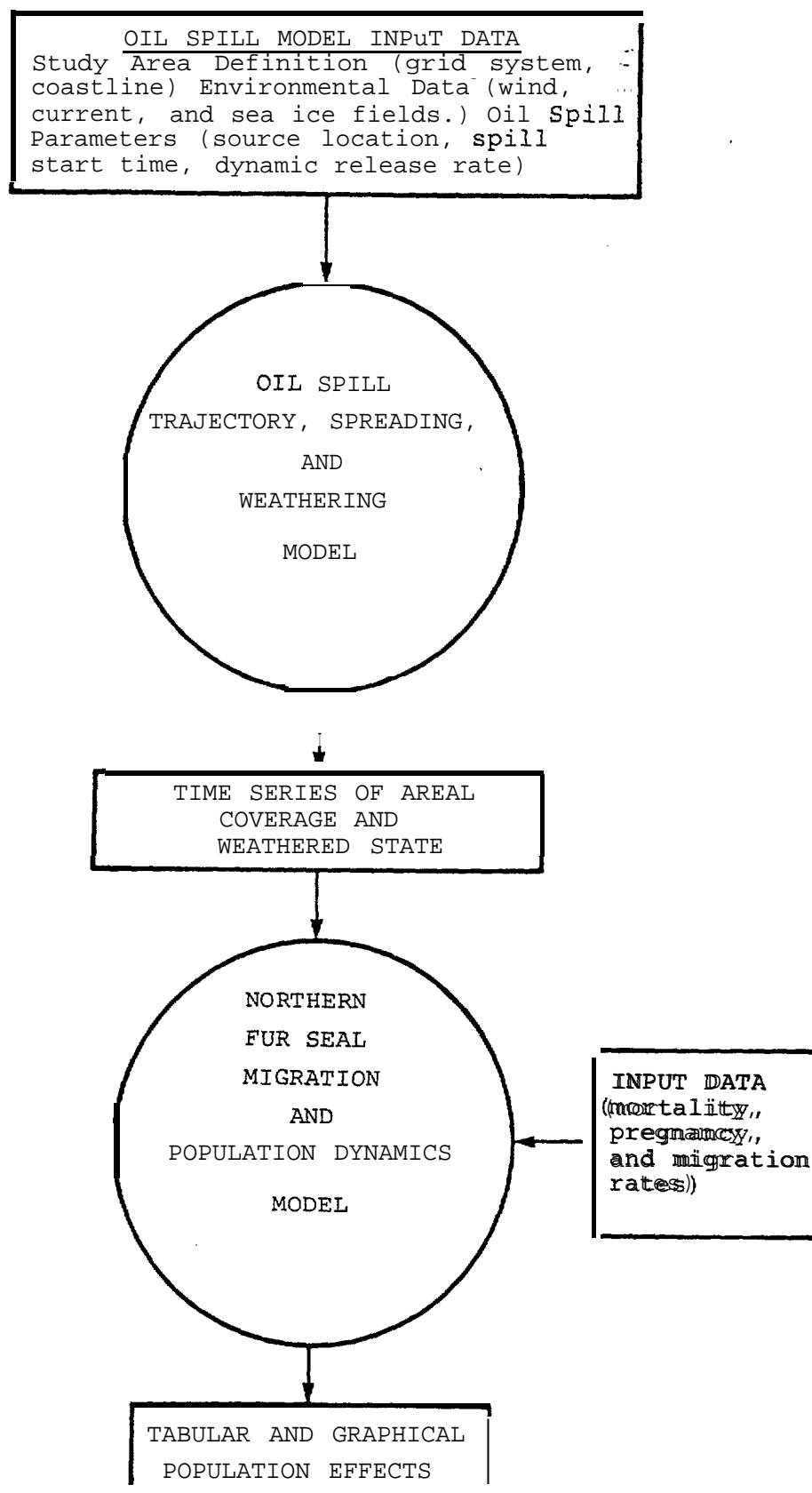


Figure 3-1. Schematic of linkages-for fur seal - oil spill interaction model system.

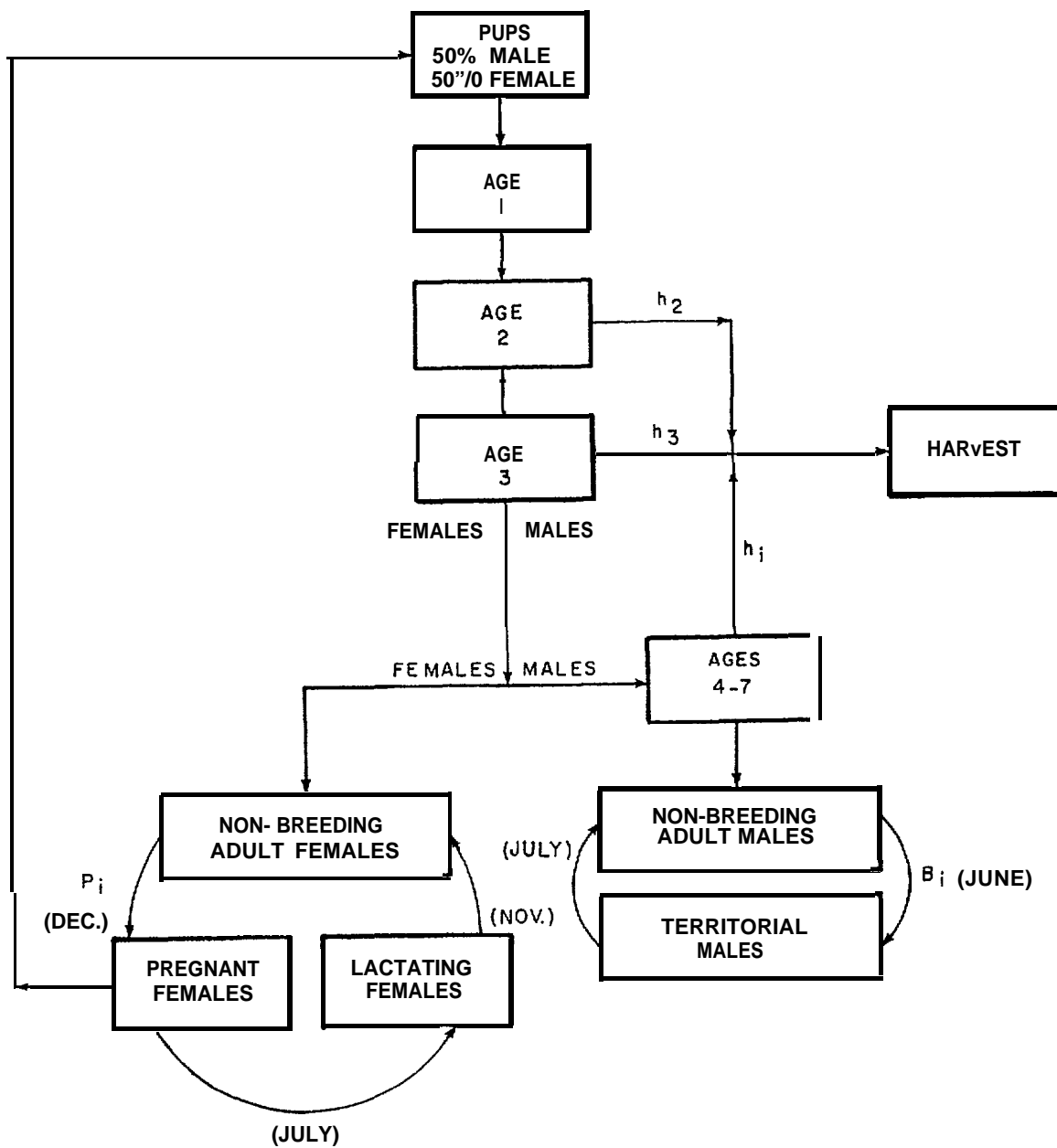


Figure 3-2. Fur Seal population model structure.

to oiling, her **pup dies** (of starvation) **as** well. Fifty percent of pups born are assigned to each sex. Pups become sexually mature at 4 years for females and 8 years for males.

Juveniles during their first **20** months at sea are subject to density dependent mortality proportional **to their** mortality as pups on land. Older juveniles and adults die at age and sex specific density independent (constant) rates,

Females older than four years become pregnant according to age-specific pregnancy rates (p_i). Pregnant seals pup in June-July, and are thereafter considered lactating seals until weaning four **months** later, **Seals** which **do** not become pregnant that year ($1 - p_i$) remain in the non-breeding adult female category.

Males between the ages of 2 and 7 years may be **harvested** at age-specific rates (h_i). Males reaching 8 years may hold territories. Age-specific fractions (B_i) of mature **males** are assigned territories in June, which they abandon in late July.

3.2 Energetic and Feeding

Energetic and feeding should be included in **the model** if the population is limited by food energy. Whether fur seal numbers are **limited by** food availability has been reviewed recently by Fowler (1985a), who concludes that the fur seal population is well **below** the environment's carrying capacity, and is not limited by food intake in either the **Bering** Sea or the North Pacific. The participants at the **NMML** meeting agreed that this evidence, plus the additional uncertainties introduced by **food** intake and energetic **submodels**, supplied sufficient grounds to exclude these components from the model. The uncertainties of energetic effects have been addressed indirectly **through** various assumed levels of recovery from oil contact, as explained in Section 7.

3.3 Migration

Arrival and Departure Times: Bering Sea and Pribilof Islands

Between December **1** and **May 1**, **nearly** all fur seals are thought to be south of the Aleutian Islands (**Kajimura**, 1980; **Bigg**, 1982). However, since **no** sampling has been performed in the Bering Sea **in** winter, and adult males are under-represented in **observations** south of the Aleutians, some males may remain in the Bering Sea at this time. The Gulf of Alaska seems to be a winter habitat for at least some adult males. While appreciative of these uncertainties, all seals are assumed to be outside the Bering Sea between these dates in the model. Thus, no explicit migration simulation is required for that time. All animals remain **at** sea (feeding) until the following spring.

Seals enter the Bering Sea through **Unimak** Pass at times dependent on age, sex, and breeding condition. Since land counts on the **Pribilofs** correspond with general migration schedule given by Kajimura (1980) and Bigg (1982), it is assumed that animals enter the Bering Sea, with at least some moving directly to the **Pribilofs**. In this way, land counts over time are used to quantify arrival and departure times to and from the Bering Sea. Arrivals and departures are distributed around a mean migration time for each seal type. Between each seal's arrival and departure date, it moves within the Bering Sea, between feeding areas at sea and one of the various **Pribilof** rookeries and hauling grounds to which it was originally assigned. Specific rookery and hauling ground locations and proportionate attendance are based on land counts by rookery reported by **Kozloff** (1980, 1982, 1985).

Some seals, mostly yearlings and two-year **olds**, do **not** return to the Bering Sea, presumably remaining in the North Pacific all summer and fall (**Kajimura** 1980). The proportion of each sex/age category returning to the Bering Sea is uncertain. Assuming all adults return to the Bering Sea, the ratio of immature seals to adult seals in the NMFS pelagic collections **made** in the Bering Sea in August-September (when seal numbers peak on the **Pribilofs**) was used to calculate the portion of immature seals returning. Thus, portions of each age and sex remain outside the Bering Sea for the summer season.

Pregnant females return to land and give birth from late June through July with peak pupping in the second week of July (Bartholomew and Heel 1953). In the model, pregnant females give birth to one pup each. Specific mother-pup pairing is retained in the model. The age, in days, of the pup determines the feeding and nursing schedule of the (now) lactating female. If the pup dies, or after the **last nursing** period on land, the mother seal is considered non-breeding (until pregnancy is assigned December 31). Pups remain on the **Pribilofs** until November, entering the surf and nearshore zones beginning July 20-31 (Bartholomew 1959). Both pups and mothers go to sea at weaning and leave the Bering Sea.

Mature **males** hold territories for an average of 47 days during June and July (Peterson 1965, 1968). Non-breeding and immature seals of both sexes (age 1-3 years for females and 1-7 years for males) arrive at the **Pribilofs** and return to sea throughout the season.

Fur Seal Distribution Within the Bering Sea

In order to determine the **number** of seals affected by an oil spill, their movements within the Bering Sea while feeding must be realistically simulated. Seals going to sea from the **Pribilofs** are thought to feed within the Bering Sea for some period of time, and then return to the **Pribilofs**. Analysis of time-depth recordings of individual females (with pups) by Gentry (1984) and Gentry et al (1985) suggest that females, at least, swim directly to feeding areas, where

they dive, feed and rest for several days, and then return directly to the rookery to nurse. The observed transit times out and back were all less than 27 hours. Individual females seem to return repeatedly to the same feeding areas, while there is great variation from one individual to the next in where they feed.

To model these **movements**, potential feeding areas have been identified and weighted by probability distributions for each age, sex and breeding condition category. When seals leave land, they move directly to **feeding** areas, remain in the vicinity for the appropriate feeding interval (moving at random within a designated area), and then return directly to their specified rookery sites.

4. Fur Seal **Model** Formulation Details

4.1 Population Dynamics

Reproduction and **Mortality** Rates

Age-specific pregnancy rates provided by York (1979) are given in Table 4-1 and Figure 4-1 and are assumed as birth rates. The pupping season, i.e. when females arrive on the rookeries, is 30 days in length, centered on July 10, based on pup counts by Bartholomew and Heel (1953, Section 4.2.1). The sex ratio at birth is assumed 1:1.

In the seal population model, mortality is age and sex specific. Total mortality rate is the sum of natural mortality, harvest rate (males only), and **mortality** due to entanglement in fishing gear. Natural mortality rate estimates by age and sex are available from several recent sources (Lander, 1979b, 1980a, 1981; Smith and Polacheck, 1981; Eberhardt, 1981; Lander and Kajimura 1982). Those of Lander (1980a, 1981, Figure 4-2 and Table 4-1 are used in the model, after correction for harvest rates (not included here as part of "natural" mortality). Mortality due to predation by killer whales, sea lions, arctic foxes (pups), etc. and due to parasitism and disease is assumed to be included in the natural mortality estimates. Constant mortality rates, such as those of Lander (1980a, 1981), assume that mortality is independent of population density. All populations, including fur seals, must have some density dependent control, or populations would increase indefinitely or decrease to zero. Smith and Polacheck (1984) and Fowler (1984, 1985a) have recently reviewed the evidence for density dependent control of the Alaskan fur seals. Density dependent mortality has been best demonstrated for pups on land and for juveniles (less than 2 years old), and so density dependent relationships for these age groups are included in the model.

The mortality of pups on land appears to increase with increasing numbers of pups counted in the **rookeries** (Lander 1979, Swartzman 1984). In the model, natural mortality rate of pups on land is

Table 4-1.

pregnancy rates (York, 1979), age-specific natural mortality rates (Lander, 1980a, 1981) and **harvest** rate on immature males (Lander, 1980a) used in the population dynamics model. The * indicates rates which are density dependent and therefore not constants.

<u>Age</u>	% of Females <u>Pregnant</u>	Natural Survival Rate (per year)		Male Harvest Rate (per year)
		<u>Female</u>	<u>Male</u>	
1	0	*	*	0
2	0	.840	.78	.028
3	0	.920	.77	.403
4	4	.940	.76	.573
5	37	.940	.74	.147
6	70	.945	.72	0
7	80	.950	.72	0
8	85	.950	.72	0
9	87	.938	.70	0
10	88	.924	.65	0
11	88	.906	.63	0
12	88	.884	.60	0
13	87	.858	.55	0
14	84	.876	.50	0
15	81	.789	.43	0
16	77	.743	.30	0
17	71	.692	.20	0
18	63	.630	.10	0
19	56	.564	0	0
20	47	.490		
21	37	.411		
22	26	.330		
23	11	.300		
24	0	.250		
25	0	.200		
26	0	.150		
27	0	.100		
28	0	.050		
29	0	0		

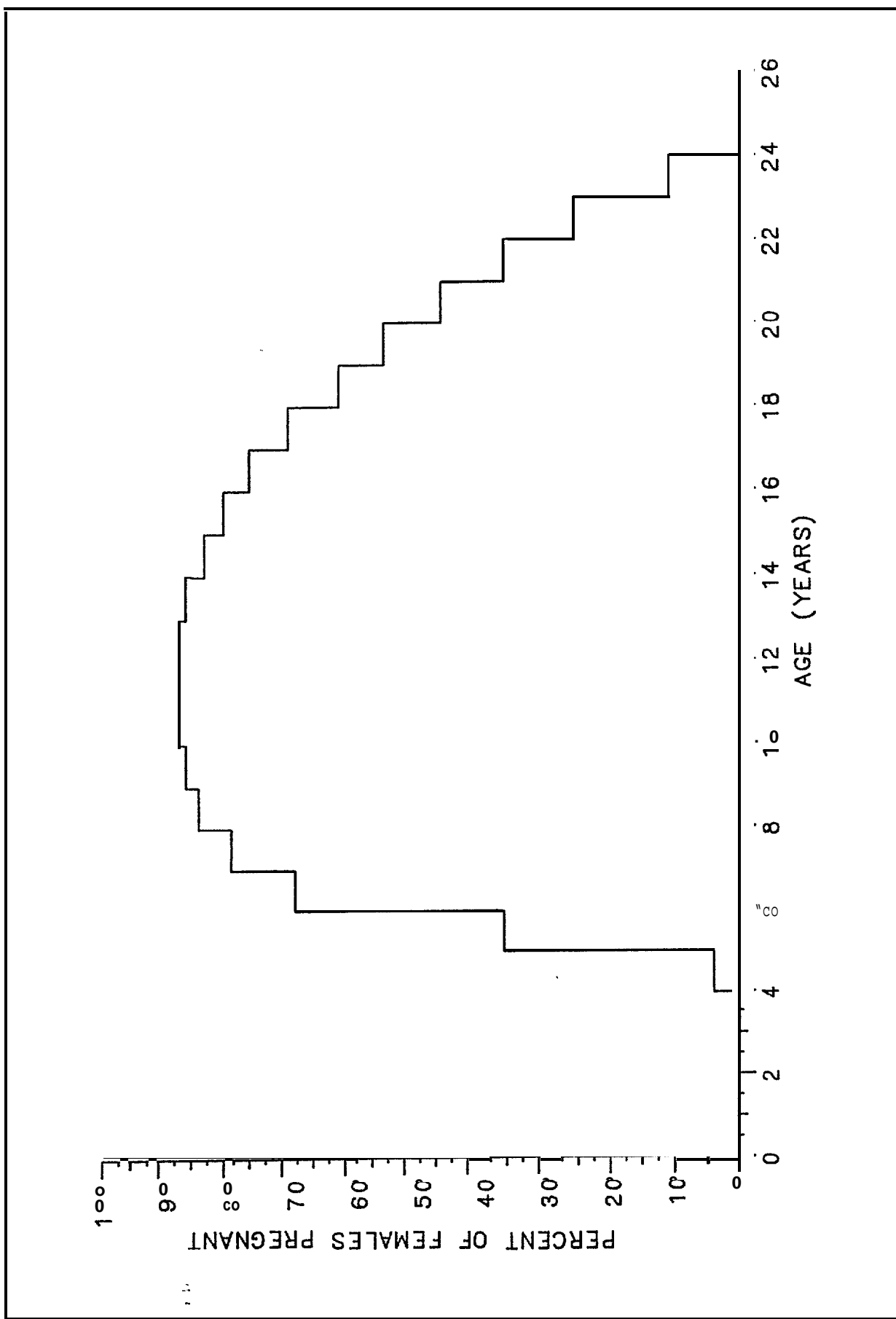


Figure 4-1. Pregnancy rate versus age.

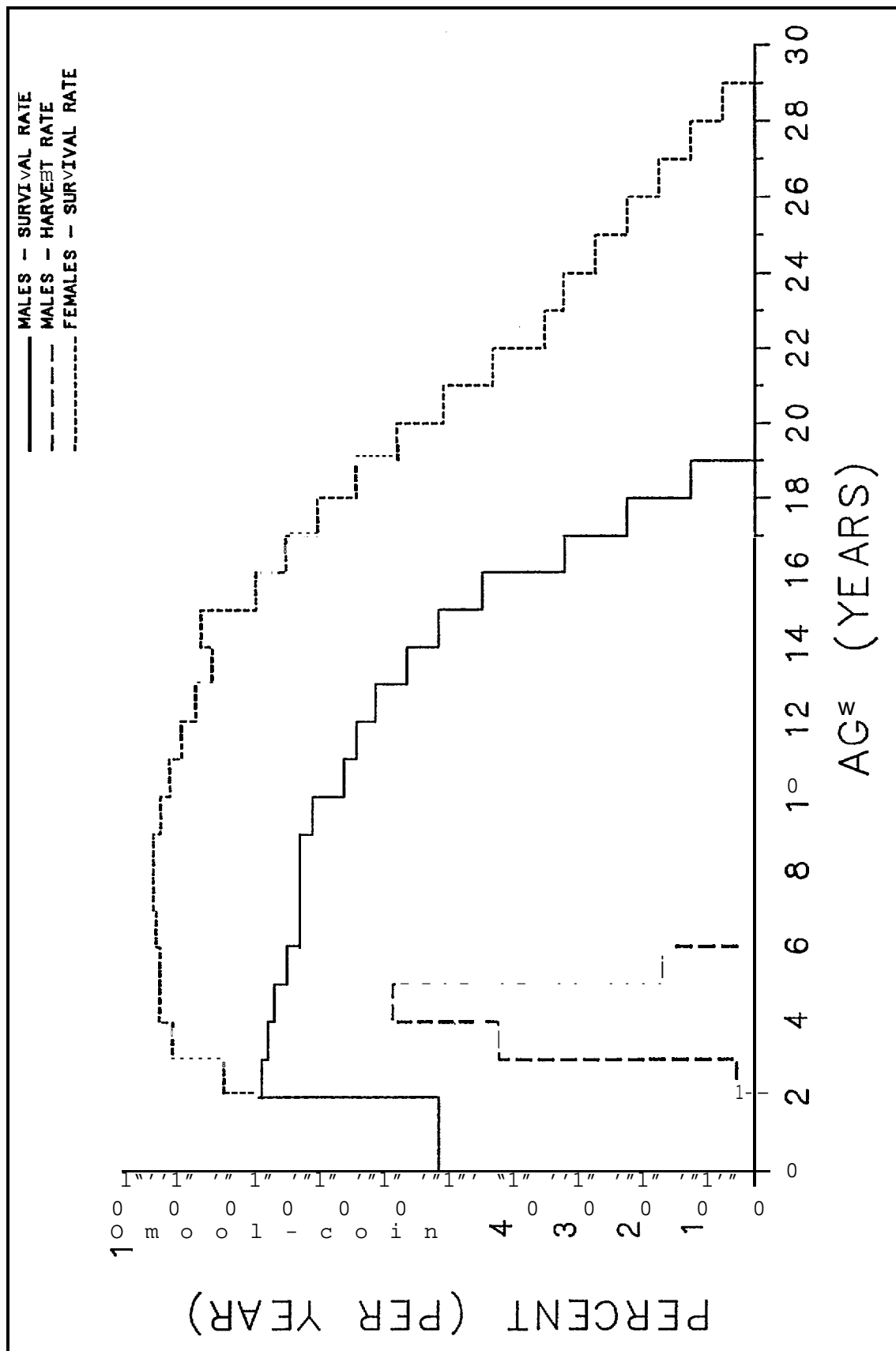


Figure 4-2. Natural survival and harvest rates as functions of age and sex (after Lander, 1980a, 1981).

a function of the number of pups born, following the functional relationship drawn by Swartzman (1984, line SL in Figure 4-3).

Survival during the first 20 months at sea also appears to be related to the number of pups born, once estimates of entanglement mortality are accounted for (Fowler, 1985b). Chapman (1961), Lander (1979b), and Eberhardt (1981) found evidence of juvenile density dependent survival in earlier analyses. The model uses the linear regression of Lander (1979b), relating survival rate of male seals less than 2 years old to survival rate while pups on land (Figure 4-4). Female juvenile seals are assumed to have the same mortality rate as males.

Lander (1980a) provides the estimates of harvest rates of male seals (Figure 4-2). These values are used in all simulations reported here. Thus, male harvest rates are assumed to be as for the 1970's, although other assumed rates may be simulated. Although females were harvested between 1956 and 1974 (commercially until 1968, and for research purposes after that), it is assumed that there will be no future resumption of a female harvest.

Comparison of Modeled and Observed Population Dynamics

The population dynamics model may be run without the associated migration component, to calculate numbers of seals over long periods of time. The model is initialized with the population distribution estimated by Lander (1980a, 1981) and the reproductive, and natural and harvest (but no entanglement) mortality rates cited above. If a simulation is then run until an equilibrium is reached (after about 300 years), the resulting population is about 1.16 million individuals with an age structure as in Table 4-2. Figure 4-5 shows the annual cycle of fur seal numbers with births occurring between June 25 and July 25. The summer increase due to births is balanced by mortality over the remainder of the year. (The maturation of immature females at age 4 causes the slight decline in the immature female curve near day 185.)

The population of 1.16 million seals is approximately equivalent to the estimated stock of 1979 (i.e., 1.15 million), as might be expected since Lander's (1980a, 1981) survival rate estimates were generated from data collected mostly in the seventies. The equilibrium population distribution in the present model is similar to Lander's (1980a) equilibrium distribution. Lander's model assumes constant survival rates for all ages, whereas the present model includes density dependent variation for ages less than 2 years. This difference accounts for the slightly different population structure. Both Lander's and the present model assume the same age-specific survival rates for ages 3 and older.

For the purposes of this model, and the interaction with oil spills, the equilibrium population of 1.16 million seals will be used in simulating a current, steady-state population. Thus, the results will reflect expectations if mortality and pregnancy rates remain constant at

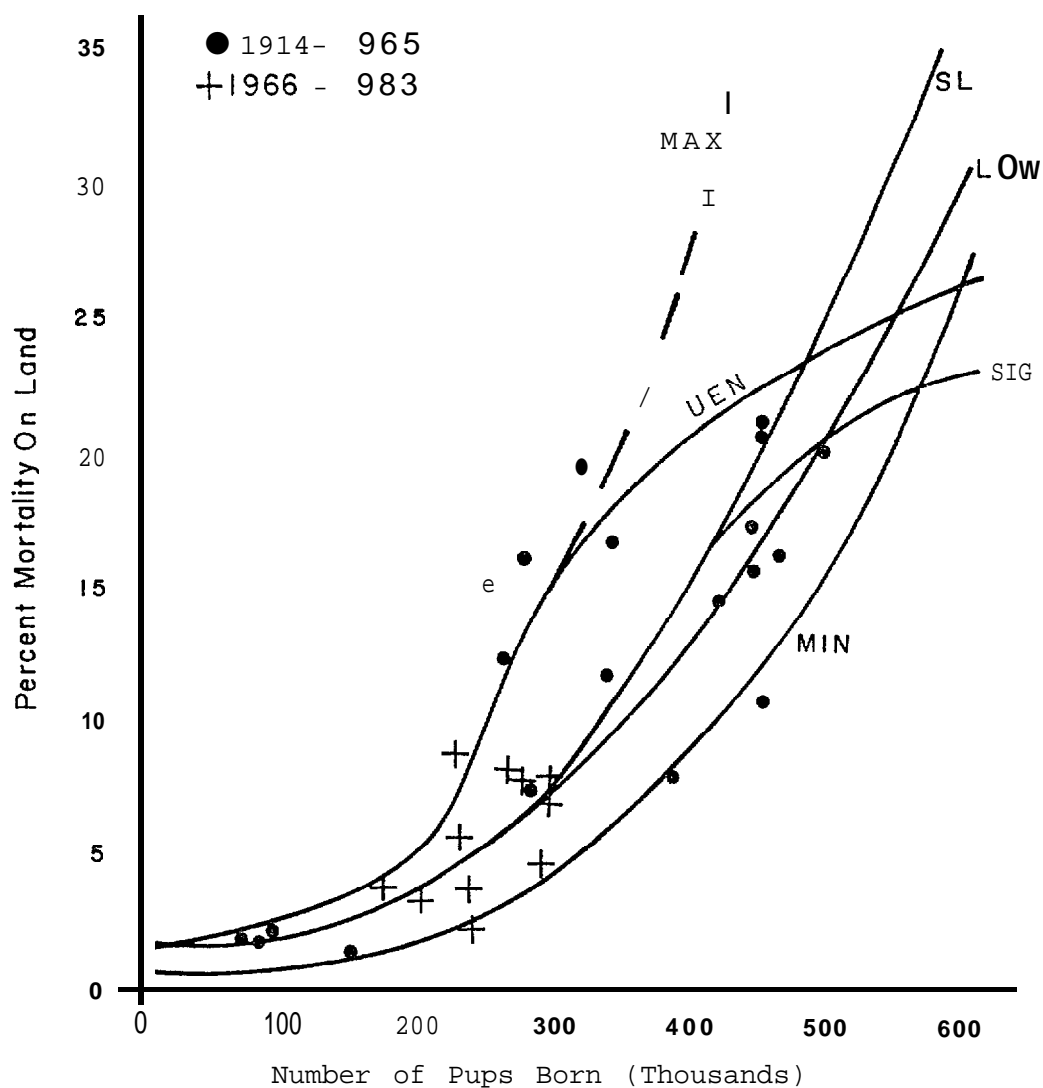


Figure 4-3. Alternate density dependent pup mortality curves. Data are from Lander, 1980b. SL is the curve drawn by Schwartzman (1984a) through the data; MAX and MIN are the maximum and minimum curves tested here; UEN is a sigmoid alternative to MAX, **SIG** is a sigmoid alternative to SL, and LOW is a lower version of SL.

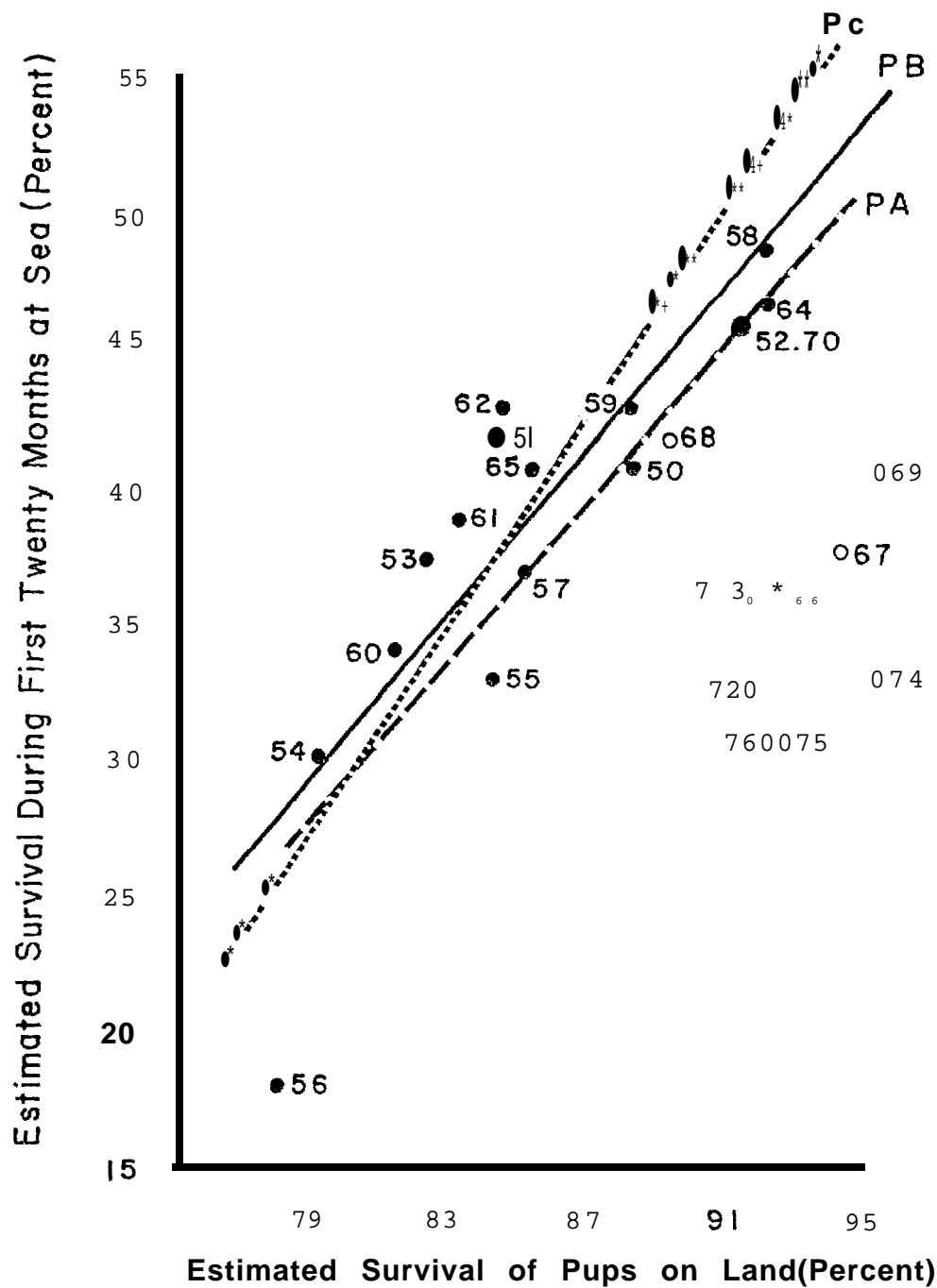


Figure 4-4. Alternate linear regressions of juvenile mortality rate as a function of pup survival. PA is from Lander (1979), regressed on the data for 1950-1970; PC is the same, but for 1950-1965 (before significant entanglement is thought to have occurred), and PB is for 1950-1965, excluding 1956.

Table 4-2 Equilibrium fur seal population numbers on January 1 resulting from 300 years of simulation using the reproductive and mortality rates cited in section 4.1.

<u>Age</u>	<u>Pregnant Females</u>	<u>Non-Pregnant. Females</u>	<u>Males</u>	<u>Total</u>
0	0.	122295.	122525.	244820.
1	0.	79709.	79084.	158793.
2	0.	58211.	56244.	114455.
3	0.	50734.	43858.	94592.
4	1893.	45440.	33433.	80765.
5	16500.	28095.	25037.	69633.
6	29392.	12597.	18303.	60292.
7	31827.	7957.	13172.	52956.
8	32294.	5699.	9431.	47424.
9	31166.	4657.	6706.	42529.
10	29074.	3965.	4575.	37614.
11	26753.	3648.	2915.	33316.
12	23998.	3272.	1791.	29061.
13	20723.	3097.	1029.	24848.
14	17391.	3312.	0.	20703.
15	13926.	3267.	0.	17193.
16	10077.	3010.	0.	13087.
17	6722.	2745.	0.	9467.
18	3917.	2300.	0.	6217.
19	2102.	1650.	0.	3751.
20	925.	1043.	0.	1968.
21	0.	0.	0.	0.
TOTAL	298679.	446704.	418103.	1163485.

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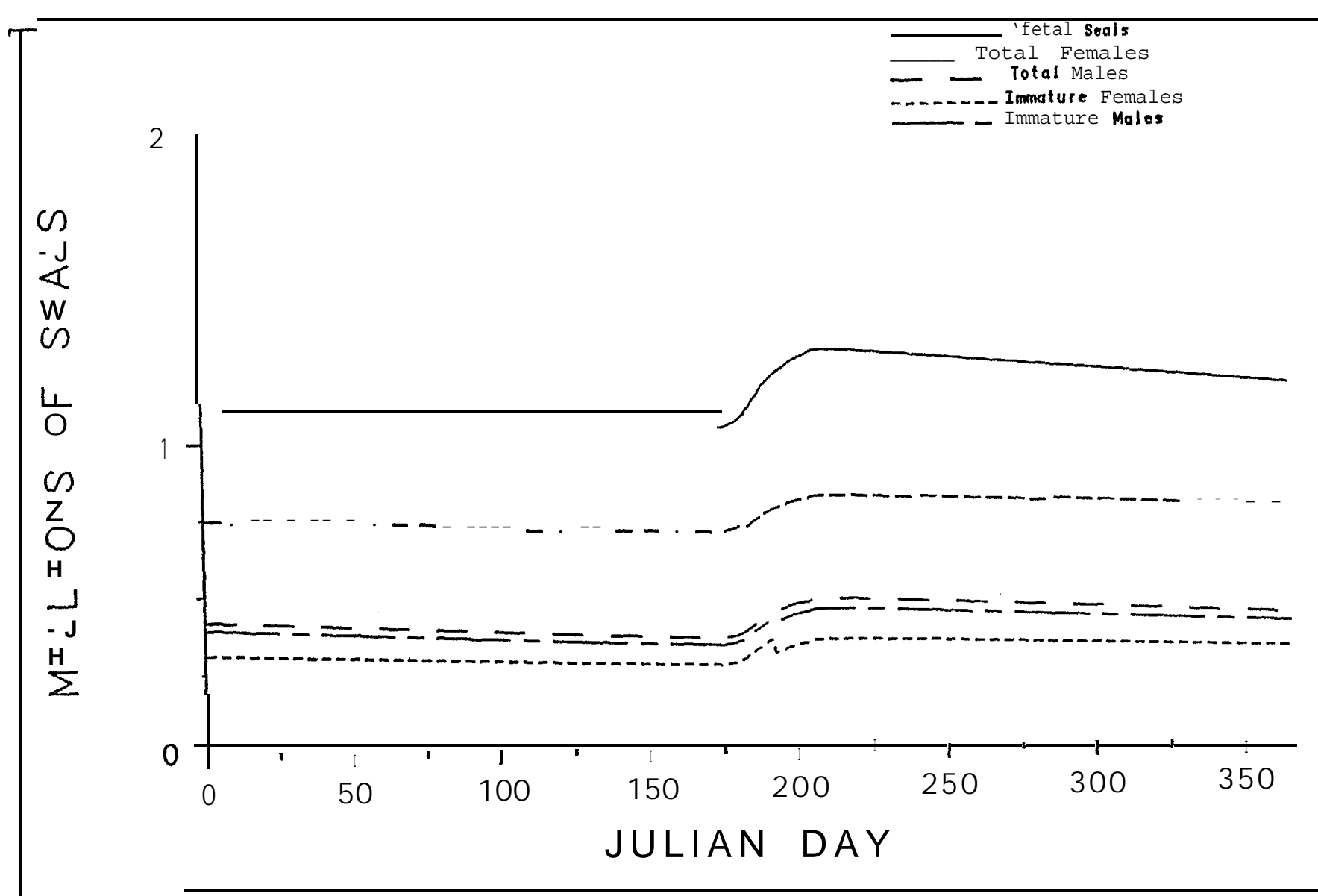


Figure 4-5. Annual cycle of modeled fur seal population numbers at equilibrium. The summer increase is due to births in late June and July. This increase is balanced by mortality over the rest of the year.

levels prevailing in the late 1970's, as estimated by Lander (1980a, 1981) and York (1979), respectively. This equilibrium population probably is well below the potential carrying capacity of the environment since the population of the 1970's (and in the model) is **not** limited by food or spatial resources (Fowler, 1985a).

In order to reflect the recent observed decline in the population, estimates of entanglement **mortality** are included. Mortality due to entanglement in fishing gear is difficult to **estimate** since **rates** of entanglement and the resulting effects are **poorly known**. Fowler (1982, 1985b) and Swartzman (1984) provide estimates of percent of the population entangled, and Swartzman presented a model of mortality rate as a function of entanglement. Fowler (1985b) has argued that entanglement can account for the current population declines observed in the Alaskan Fur Seal. This decline coincides with the increased usage of plastic fishing gear and **observations** of entangled seals. Participants at the NMML meeting agreed that the probable cause of the decline is entanglement, but more study is required and other causes remain under consideration (e.g. sublethal pollutant effects).

Entanglement mortality rates were estimated using the analysis of Fowler (1985b). Fowler found that the strong correlation between pup survival on land and male juvenile survival over the first 20 months at sea that exists when data for 1950-1965 is considered, breaks down when the data of recent years is added. Using a regression for 1950-1965 to calculate an expected juvenile survival rate, the discrepancy between the observed and expected is linearly correlated with the rate of entanglement **observed** in the male **harvest**. The current entanglement rate (0.4% per year) corresponds to a discrepancy of -0.15. This value is used in the present model as additional mortality of juveniles **due** to entanglement for up to 2 years of age (i.e., 0.15 is added to the natural **mortality** rates cited above to yield total mortality over 20 months). Fowler (1985b) also estimates an entanglement mortality rate for seals 2 to 3 years old from the frequency of entanglement of males in the **harvest** by age. This rate of 4.9% per year is multiplied times natural **mortality** to give total mortality for both males and females of 2 to 3 years of age. By using the same entanglement mortality rates for males and females of a given age, we are assuming that entanglement rate and subsequent **mortality** are functions of age of seals, and not their size relative to the plastic debris present in the Bering Sea and North Pacific. Thus, this is a **conservative** assumption since female entanglement mortality could be higher than that for males of the same age owing to their smaller size.

Estimates of entanglement rates and **mortality** are not available for older seals. Therefore a range of rates has been tried, and the resulting simulated population rate of decline compared to the observed rate. Since younger animals appear to suffer higher entanglement **mortality** rates (Fowler, 1985b), adult entanglement mortality is not **likely** to be greater than the 4.9% rate of 2 and 3 year **olds**. The resulting decline for the range of 0% to 5% is shown in Table 4-3. As may be seen in Table 4-4, the assumption that adults and 2 to 3 year **olds** suffer the same **5% mortality**

Table 4-3. Resulting annual population decline over **the** first ten years after initializing the population at equilibrium (1.16 million seals) as a function of the rate of entanglement **mortality** of seals over 3 years of age. Juveniles are assumed to suffer an additional 15% mortality over their first 20 months at sea and **5%** mortality during the year **from** 2 to 3 years of age (**Fowler, 1985b**) .

Entanglement mortality for >3 years <u>(% per year)</u>	Resulting Population Decline <u>(% per year)</u>
0.	3.1
1.	3.7
2.	4.4
3.	4.8
4.	5.5
5.	6.2

Table 4-4. Observed (estimated) fur **seal** stocks (in August) by year from 1979 to 1985, observed population decline, and model population (Jan. 1) with entanglement included starting from the equilibrium (1979) population. Estimates for 1979 to 1983 are **from** Briggs and **Fowler** (1985). Those for 1984 **and** 1985 were calculated from estimates of the number of pups born on St. Paul Island those years (173,274 and 176,992, respectively, **C.W. Fowler**, pers. **comm.**) following the procedure of **Kozloff** et al (1985). Entanglement mortalities assumed in the model are: an additional 15% mortality of juveniles at sea up to age 2 years over and above calculated juvenile mortality based on pup mortality on land (**Fowler, 1985b**); 5% mortality for age 2-3 years (**Fowler, 1985b**); and 5% mortality for ages >3 years. The rate of decline of the model population is 6.2% per year.

<u>Year</u>	<u>Observed Stock Estimate</u>	<u>Observed % Decline From Previous Year</u>	<u>Model Population With Entanglement</u>
1979	1153826	6.7	1163485
1980	1100545	4.6	1071621
1981	998266	9.4	998510
1982	931642	6.7	936371
1983	870900	6.5	882037
1984	861500	1.1	832778
1985	808100	6.2	785066
1986			738731

rate **due to** entanglement, results in a 6.2% per year population decline and a close match to the stock estimates for 1979-1983. The stock estimate for 1984 **is** suggestive of a slowing of the decline, but the 1985 estimate is **still** 6.2% lower. Thus, the 6.2% decline is assumed to continue to 1986 in the model as a extreme-case assumption. To the extent that the decline has slowed **in** the last 2 years, **the modeled** 1986 population is slightly underestimated (by about 2%). The decline in the model population from 1979 to 1986 is plotted in Figure 4-6a.

Figure 4-6b shows the fate of the population after 1986 if current entanglement mortality rates and the age specific natural **mortality** rates remain constant for the next 100 years. The curvature is due to the density-dependent functions for pup and juvenile mortality rates. The model estimates that the fur seal population will decline to 4000 individuals after 100 years at these rates, and to extinction **in** 140 years. Obviously, this model result accentuates the need for further study of entanglement mortality, and other possible causes for the recent decline.

In assessing the effect of oil spills on the fur seal population, the simulated 1986 population was used in addition to n-ins with the 1.16 million equilibrium population. Figure 4-7 shows the annual cycle of the 1986 population and Table 4-5 gives the age structure on January 1.

The linear relationship between juvenile survival and **pup** survival on land (Figure 4-4) provided by Lander (1979b) includes data after 1965 (to 1970), **when** entanglement is believed **to** have become significant (Fouler, 1985b). Thus a regression (using the **methodology** in Fowler, 1985b), including only 1950-1965 data, was compared to **the** results using Lander's equation (Figure 4-4). In addition, the pup mortality curve as a function of number of pups born was varied within the range of possibilities seen in the data (Figure 4-3). The resulting equilibrium populations are tabulated in Table 4-6. Varying the regression equation used for juvenile survival from the 1950-1970 line of Lander (1979b) to that for 1950-1965 increased the equilibrium population slightly. Varying the pup mortality tune, which is associated with much more variability in the data, has a larger effect. However, the highest population size obtainable, within the range of pup and juvenile mortalities observed, is 1.7 million seals. This value is short of the 1950's stock size of just over 2 million. Therefore, the estimated mortality rates used here **may** be higher than those prevailing in the 1950's, or reproductive rates may now be lower than previously occurred. It is also likely that **mortality** and reproduction rates of older seals vary with population densities, although evidence for this has not been **demonstrated** to date (Fouler, 1984).

In an attempt to simulate the 1950s population of about 2.2 million seals, earlier estimates of pregnancy and mortality rates were sought. The juvenile **mortality** curve which does **not** include recent entanglement (line PB in Figure 4-4) was used in all cases. Pup **mortality** was assumed to be as tune SL, Figure 4-3.

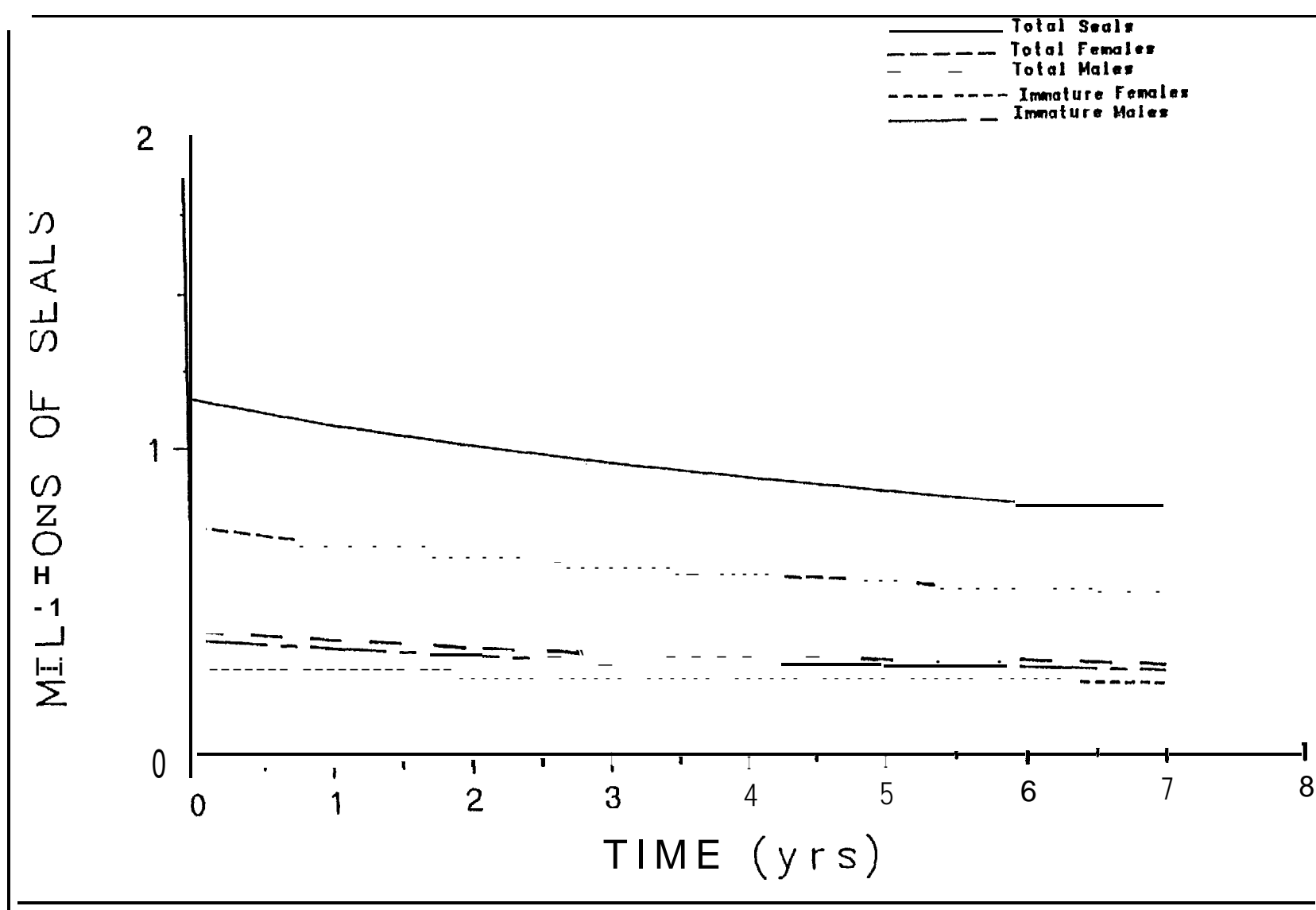


Figure 4-6a. Simulation of population numbers between 1979 and 1986, assuming constant entanglement mortality rates at current levels throughout the period.

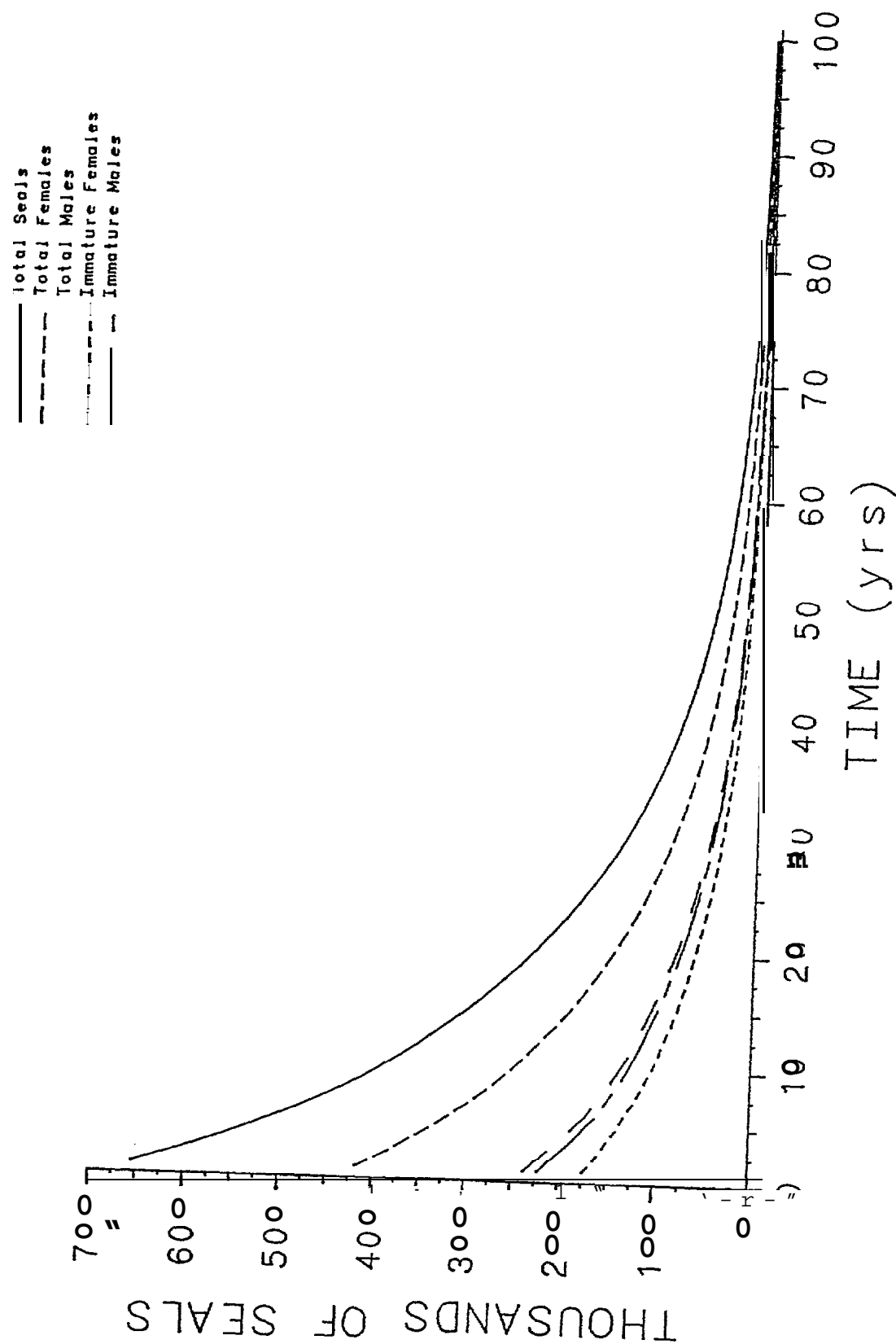


Figure 4-6b. Simulation of population numbers for 100 years following 1986, assuming constant entanglement mortality rates at 1986 levels throughout the period. Pup and juvenile mortality is density dependent in this simulation, but mortality rates of seals older than three years are held constant at present levels.

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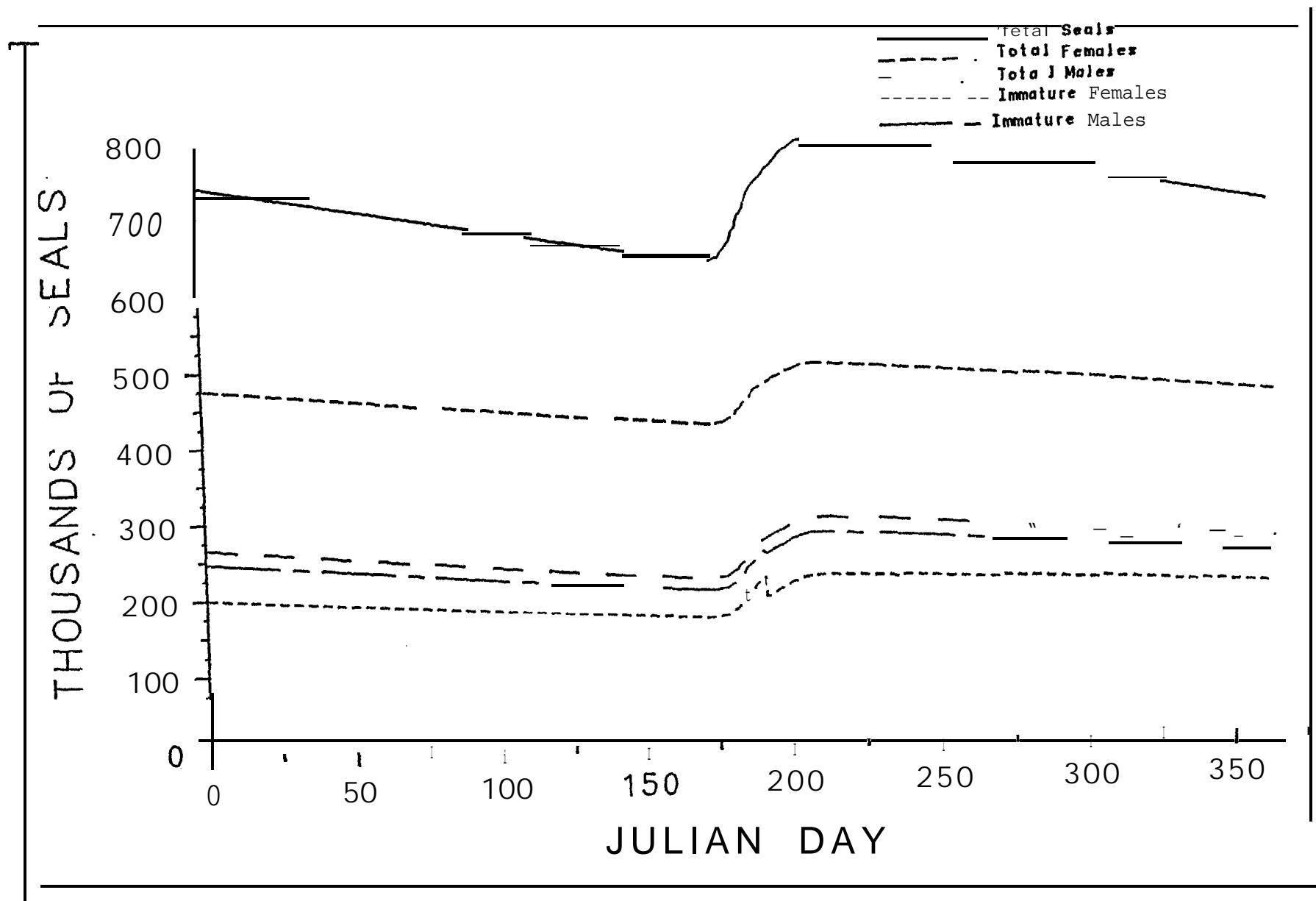


Figure 4-7. Annual cycle of population numbers for the simulation of 1986.

Table 4-5. Simulated 1986 fur seal population numbers by age, reproductive condition, and sex on January 1.

<u>Age</u>	<u>Pregnant Females</u>	<u>Non-Pregnant Females</u>	<u>Males</u>	<u>Total</u>
0	0.	84319.	83748.	168067.
1	0.	49498.	51713.	101211.
2	0.	35653.	33593.	69247.
3	0.	29818.	26317.	56135.
4	1105.	26530.	19161.	46796.
5	9098.	15492.	14261.	38851.
6	15310.	6562.	10260.	32132.
7	16957.	4239.	7013.	28209.
8	20566.	3629.	6008.	30204.
9	21736.	3248.	4709.	29693.
10	20343.	2774.	3201.	26317.
11	18690.	2549.	2042.	23281.
12	16775.	2288.	1254.	20317.
13	14442.	2158.	723.	17322.
14	11963.	2279.	0.	14242.
15	9665.	2267.	0.	11932.
16	7105.	2122.	0.	9227.
17	4660.	1903.	0.	6563.
18	2751.	1615.	0.	4366.
19	1464.	1150.	0.	2614.
20	650.	732.	0.	1382.
2 1	231.	394.	0.	625.
22	0.	0.	0.	0.
TOTAL	193510.	281219.	264002.	738731.

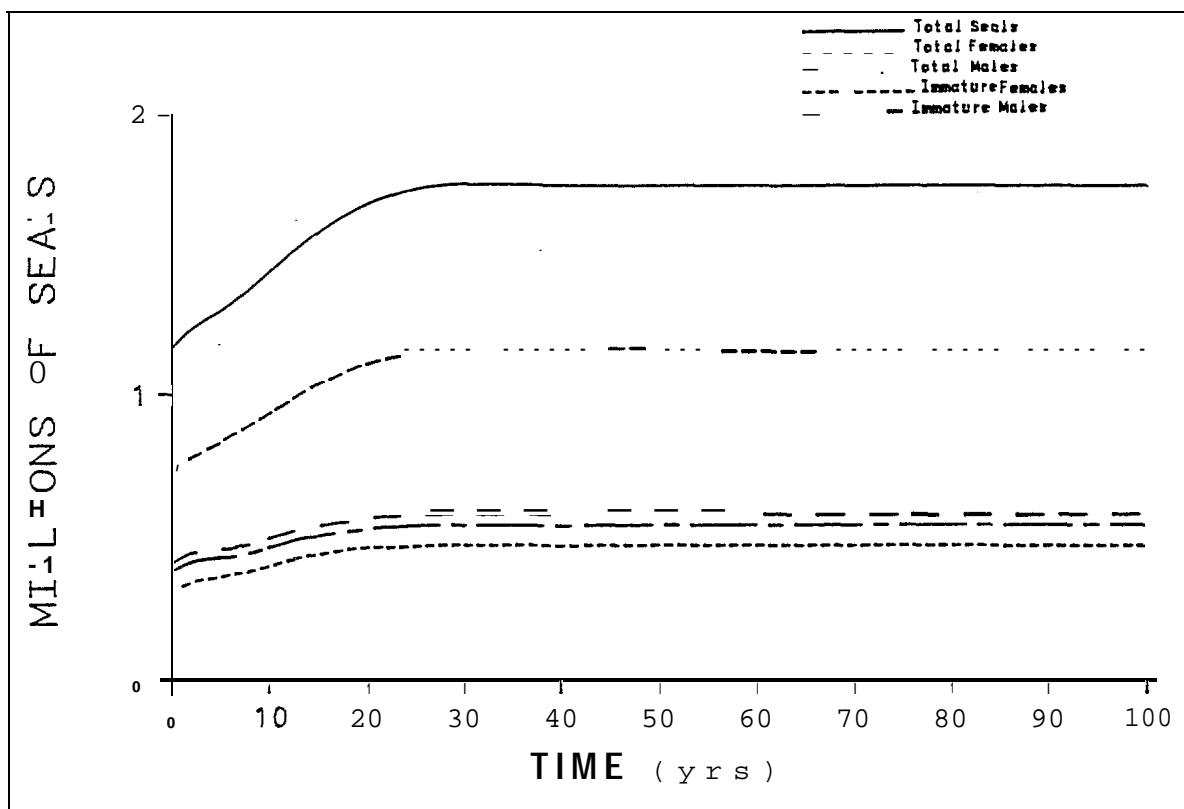
Table 4-6. Equilibrium fur seal population (thousands) resulting from variation in the density dependent pup and juvenile mortality functions. The labels **MAX**, **UEN**, **SIG**, **SL**, **LOW** and **MIN** refer to the hand-drawn curves in Figure 4-3 relating pup mortality to number of pups born. The curve labeled **SL** is the line drawn by **Swartzman (1984b)** through the data, Juvenile survival rate as a function of pup survival rate is shown in Figure 4-4. The line labeled **PA** is Lander's (1979a) regression for the data 1950-1970, **PC** is the same, but for 1950-1965 (before entanglement was significant, **Fowler 1985b**), and **PB** is the 1950-1965 data excluding 1956.

Juvenile Survival	Years Included	1950- 1970	1950-1965 (excl. 1956)	1950- 1965
Vs .				
Pup Survival	Slope Intercept	1.425 -0.83	1.467 -0.85	1.977 -1.29
	Label	PA	PB	PC
Pup Mortality	MAX	952	990	1030
	UEN	930	964	1005
Vs .	SIG	1171	1224	1284
# Pups Born	SL	1163	1253	1316
	LOW	1183	1263	1343
	MIN	1580	1668	1738

Three alternate data sets of pregnancy rate as a function of age were tried. Only those rates for females between ages 4 and 11 were varied, since alternate estimates for older ages were not found. From Chapman (1961), pregnancy rates for animals collected in 1958 and 1959 were averaged. From Chapman (1964), estimates for the years 1958 through 1961 were used, as reported in Smith and **Polacheck** (1981). For both these data sets, pregnancy rates of 4 to 6 year olds were significantly higher than the estimates of York (1979) which included data from later years of collection. However, this change in pregnancy rate had relatively little effect on the resulting equilibrium population size (up to a difference of 10,000 seals, just under 1% of the total population). The third data set tried was that based on Japanese collections of 1958 through 1960, as reported by Smith and **Pollacheck** (1984). These rates were 54%, 86%, 87%, 94%, and 95% for females aged 4 through 9 years. The resulting population size using this data was 1.28 million seals, only 2% higher than the 1.25 million population obtained using York's (1979) lower pregnancy rates. Since the Japanese collection estimates are the highest observations which are reasonable, it is not **possible** to account for the higher 1950s population size by a change in pregnancy rates. Therefore, mortality rates must have been lower in the 1950s than those used in the standard equilibrium model of 1.16 million seals.

Mortality rates of juveniles less than 2 years of age are the least well known rates for the various age classes. In the standard model, female juvenile **mortality** is assumed to follow the same density dependent function as estimated for males. However, Chapman (1961, 1964) provides evidence that female juveniles may have higher **survival** rates than males, at least during the 1950s **when** the population was at its highest level. Based on tagging returns and accounting for lost-tag biases, **he** estimated that female survival to age 3 averaged 1.64 times that of males using 1950s data. However, based on other analyses, Chapman (1964) felt that a ratio of 1.27 was a more realistic estimate. His various estimates, in fact, fall into two **groups**: one set averaging 1.27 and the other averaging 1.74, with more data supporting the latter and Chapman preferring the former as more realistic. Thus, both values were tried here. Since the ratio of female to male **survival** from age 2 to 3 is 1.08 (Table 4-1) and pups of both sexes are assumed to suffer equal mortality while on land, the ratios of survival to age 3, 1.27 and 1.74, are equivalent to 1.2 and 1.6 times as many females as males surviving their first twenty months at sea, respectively. In the standard population model **where** female survival to age 2 is assumed **equivalent** to male survival, the ratio of female to male survival to age 3 is 1.08. Assuming female juvenile survival is a constant proportion of **male** juvenile survival at all population densities, line **PB** (Figure 4-4) for male juvenile **survival**, tune SL (Figure 4-3) for pup mortality, and the adult mortality rates in Table 4-1, the population model was run using these two possible ratio values for female to male survival while juveniles at sea. Figure 4-8a and b show the increase from the 1.16 million equilibrium population and the resulting steady-state populations.

(a)



(b)

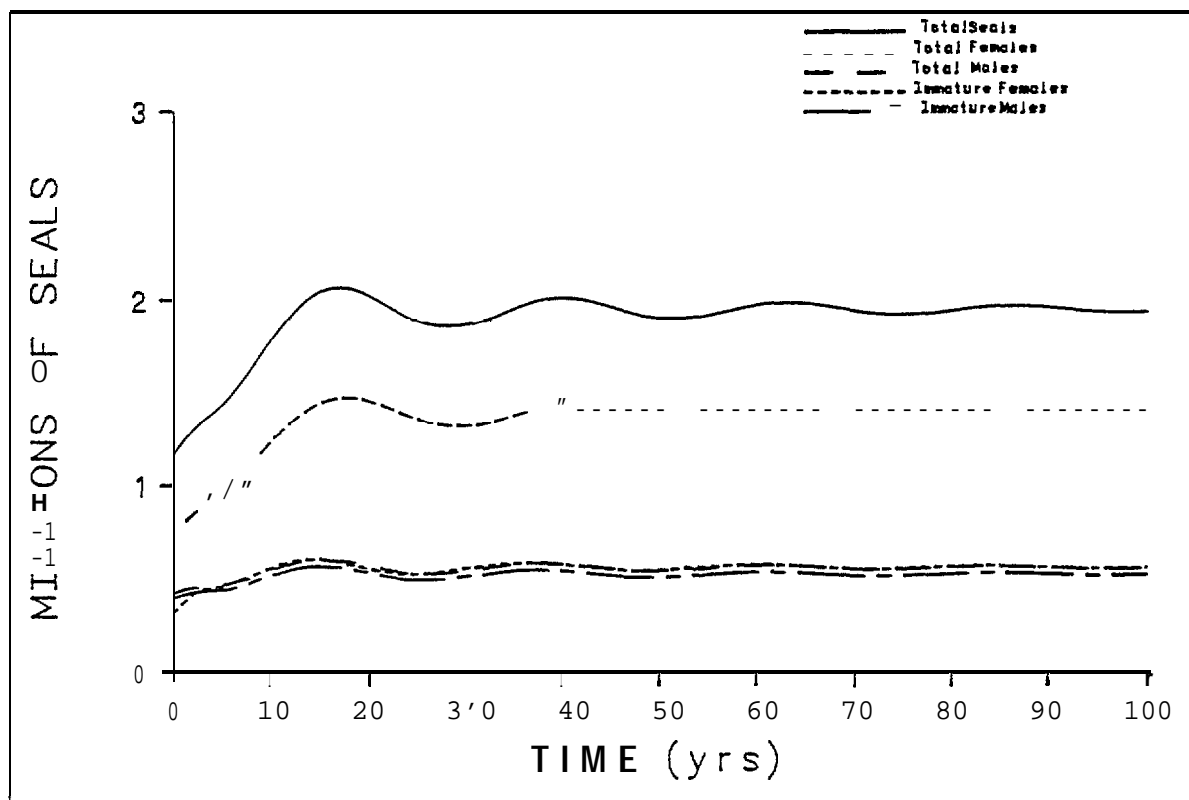


Figure 4-8. Simulation of the 1950s fur seal population assuming the ratio of female to male survival to age three is (a) 1.27, (b) 1.74 (initialized with 1.16 million equilibrium population).

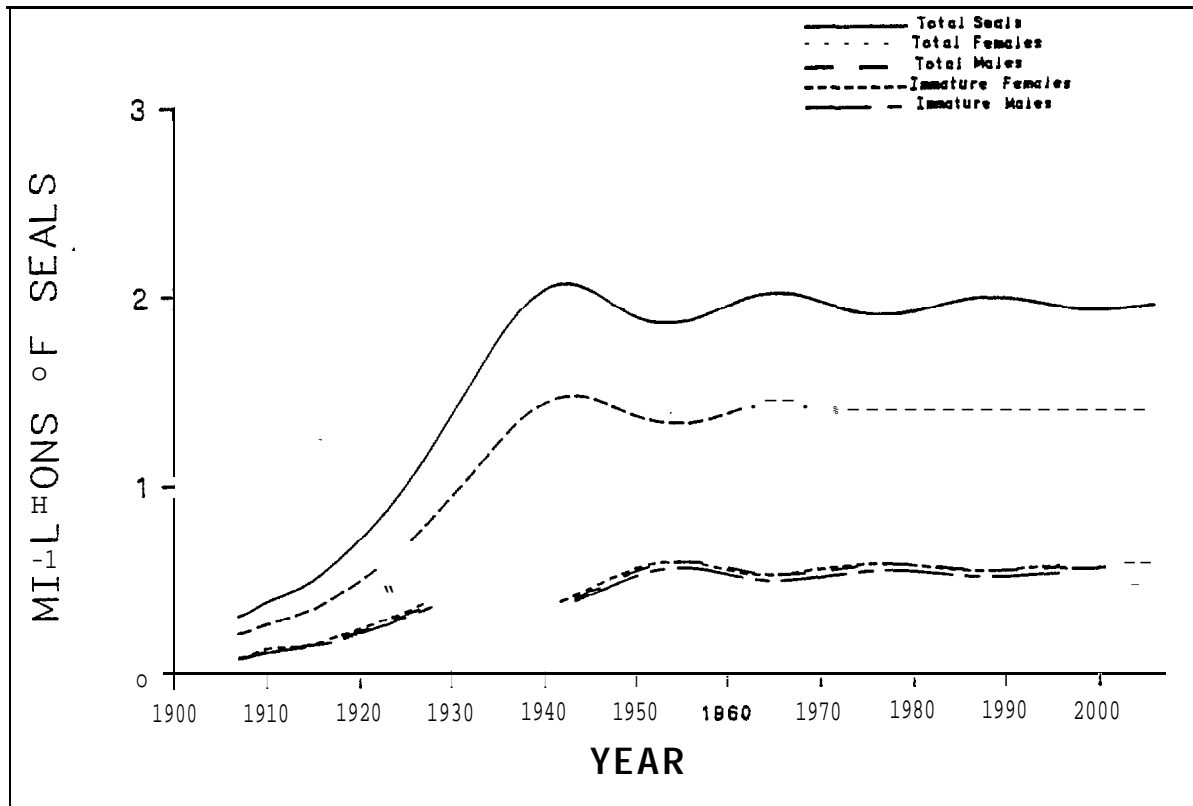
Assuming a female to male juvenile survival ratio of 1.27 over 3 years increases the equilibrium population substantially, to 1.73 million seals and 442 thousand pups born each year (Figure 4-8a). This level is still somewhat short of **the 1950s population level** estimates of 2.0-2.2 million seals and 550 to 580 thousand seals born (**Briggs and Fowler, 1984**) . If the ratio of 1.74 is assumed for female to male juvenile **survival**, the population initially oscillates between 1.9 and 2.0 million seals with 491 to 573 thousand pups born each year, and after 50 years settles to 1.95 million seals and 525-555 thousand pups born per year (Figure 4-8b). The oscillations damp out after 200 years of simulation to 1.95 million total seals and 540 thousand pups born **per year**. The number of pups born in this model population is close to estimate pup counts between 1949 and 1958, but the total population is just slightly less than that estimated by **Briggs and Fowler (1984)** for the 1950s. If the female to male juvenile ratio is assumed to be 1.82, the equilibrium population is increased to 1.8 to 2.1 million seals, oscillating on a 22 year **cycle** (not shown) with 548 to 645 thousand pups born per year. While this population size is closer to **Briggs and Fowler's** estimates, the pup numbers **are too high**, Since population estimates are based on pup **numbers**, the closer match to **number of pups born** is probably the better simulation of the 1950s population (i.e., Figure 4-8b).

A simulation was run using 15% of the 1950s equilibrium population of Figure 4-8b as the initial population size, thereby initializing with a population level equivalent to the estimated total size in 1912. The resulting population model response is shown in Figure 4-8c and d. Both total population numbers (Figure 4-8c) and number of pups born (Figure 4-8d) agree with **estimates** of field populations up through **the** start of the female **harvest** in 1956, which is not simulated in the present model. The rate of increase in pup production matches observations extremely well. Estimated pup production in the field remains in agreement with the model until 1960, when **the** effects of female **harvest** were first felt (Figure 4-8d). Thus, the mortality and pregnancy rates used in the **model** appear to be very realistic, at least for the first half of the century before female harvest and entanglement, or other causes of the current decline.

The simulated population in Figures 4-8b, c and d oscillates on a 23 year **cycle**. Allen and **Basasibwaki** (1974) have shown that the period of major oscillations in model populations is equivalent to twice the average age of reproduction, which for fur seals is **about 11 years**.

The oscillation is induced in the **model** by the differential density-dependent **survival** rates of juvenile males and females. Since **survival** rates of older females are higher than those for males (Table 4-1), the assumption of higher rates for female juveniles seems reasonable. However, **the** density dependence of female juvenile survival is unknown, since the only data **available** is from a single population size. The difference between male and female density dependence determines the amplitude of **the oscillations in** the population, and the model is very sensitive to the **value** of this ratio. Clearly, **estimation**

(c)



(d)

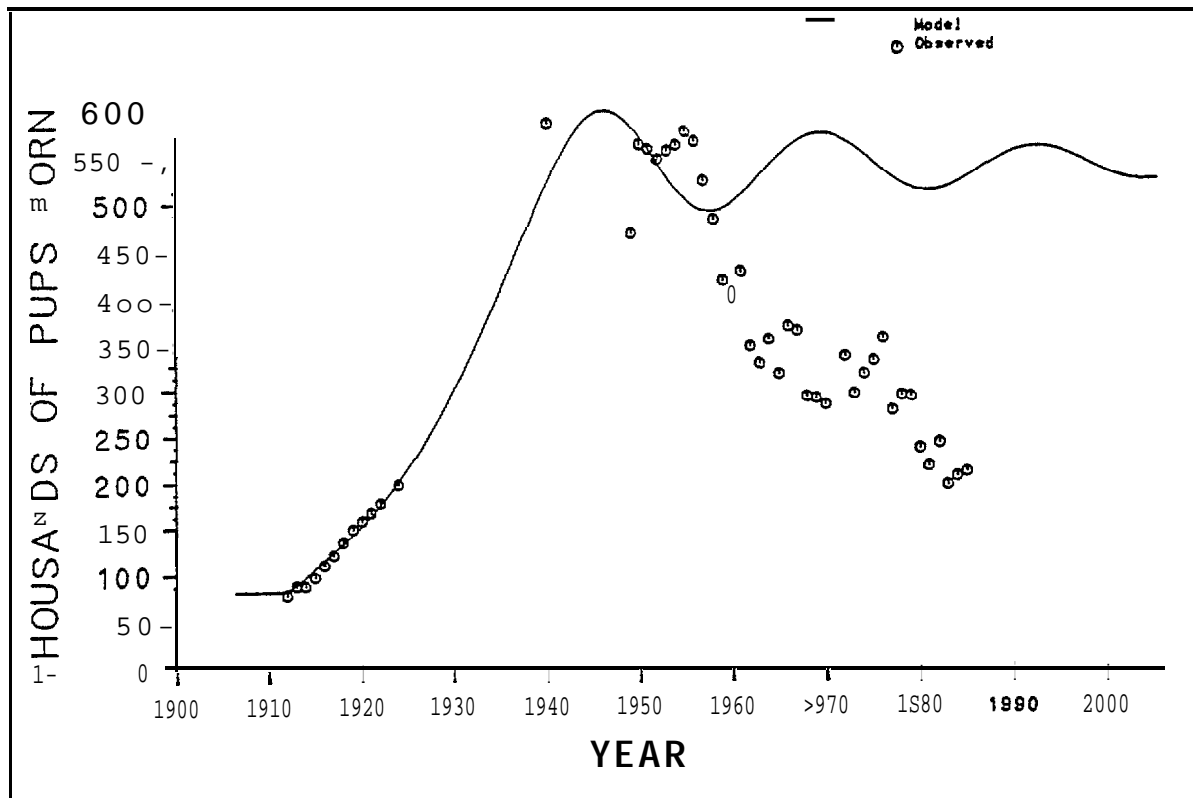


Figure 4-8. Simulation of the 1950s fur seal population and the population increase beginning in 1912 after initializing with 15% of the 1950s equilibrium population size. (c) Numbers of seals by sexual category, (d) numbers of pups born each year. The female harvest, which is not simulated, began in 1956.

of female juvenile survival at lower population sizes would increase the reliability of the model. As no estimates of female juvenile survival are available for the current population, differential survival was not assumed for the standard populations used in the oil spill runs reported here.

The **pup mortality** curve assumed in **the** model also **has** a large influence on the resulting population size (Table 4-6). Better estimates of density-dependent pup mortality rates would greatly improve the accuracy of the model. A function relating pup mortality to density on the rookeries would perhaps be more accurate than a function of total pups born, particularly if the size or **numbers** of rookeries change with changing population size.

For the simulations of Figure 4-8, harvest rates of males were assumed to be zero. However, inclusion of harvest rates up to the values in Table 4-1 does not influence the resulting population size significantly. **The** total population is reduced by less than 2%, on average, within this range of harvest rates, a level which would be undetectable in the natural population.

4.2 Migration Model

Description and Input Data

Seals enter the Bering Sea via Unimak Pass according to probability distributions which vary by sex, age, and reproductive status. Once through Unimak Pass, seals move **towards** their various destinations at estimated swimming speeds. Pregnant females and mature males proceed directly toward their respective rookeries on the **Pribilofs**. Other seal types move to the islands or to feeding areas at sea, based on probability distributions derived empirically.

Pregnant females give birth upon arrival on the **Pribilofs**. Their arrival times for pupping are assumed to be as observed by Bartholomew and Heel (1953), as shown in Figure 4-9.

Pregnant females (and other seal types are) distributed among 21 rookeries based on land counts of bulls (**Kozloff**, 1985), under the assumption that other seal types are in constant ratios to bulls from rookery to rookery. Rookery locations and **portions** of the total population identified with each are shown in Figures 4-10a and b, and Table 4-7. Pregnant females in the model swim towards their rookery destination at about 40 km per day with both direction and velocity containing a random component (**+1%** and **+10%**, respectively). The assumed velocity allows fur seals to **travel** from Unimak Pass to the rookeries in about two weeks, which is the approximate time between the maximum flux of females passing through Unimak Pass (**Bigg**, 1982) and **their** arrival on the **Pribilofs** (Bartholomew and Heel, 1953 and Figure 4-9). Thus pregnant females enter Unimak Pass over the one month

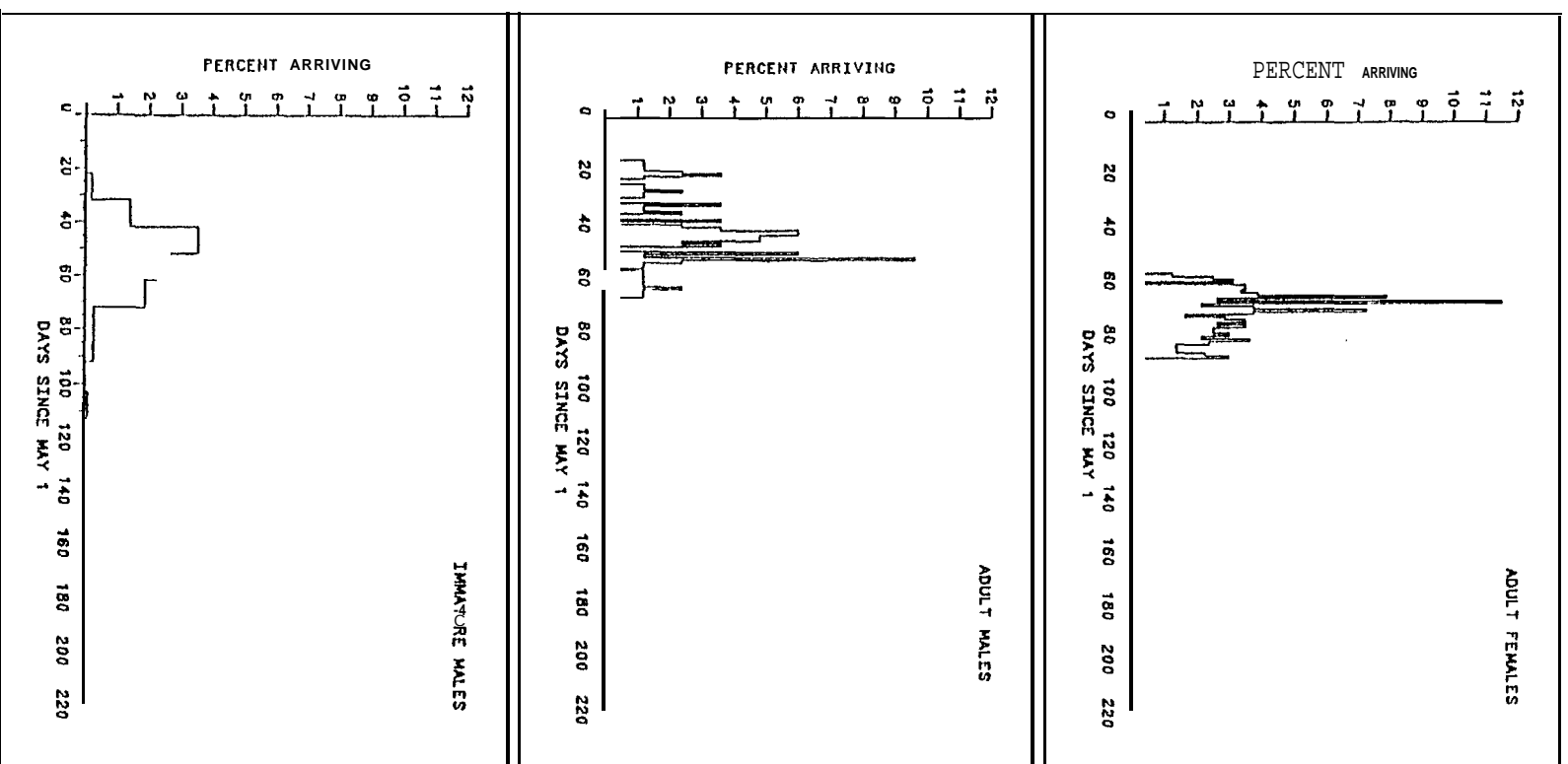


Figure 4-9. Distribution of arrival times of fur seals on the Pribilof rookeries assumed in the migration model.

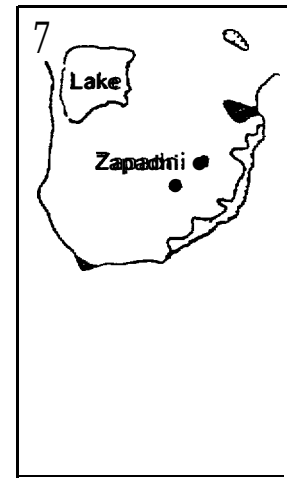
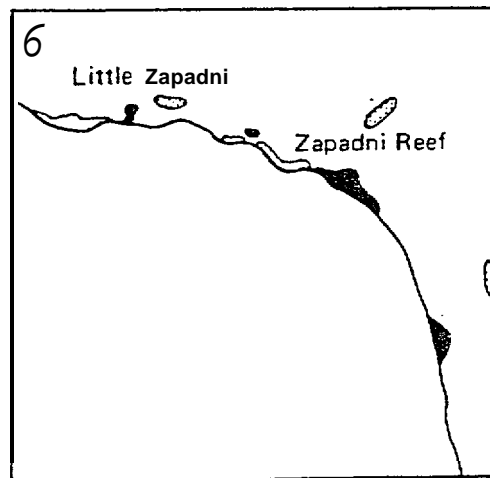
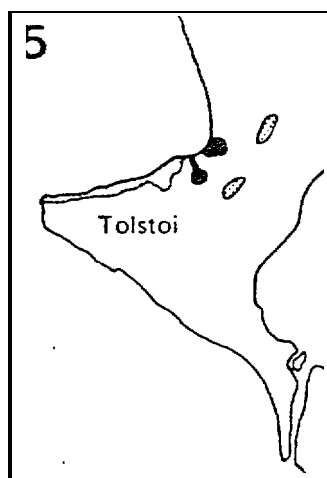
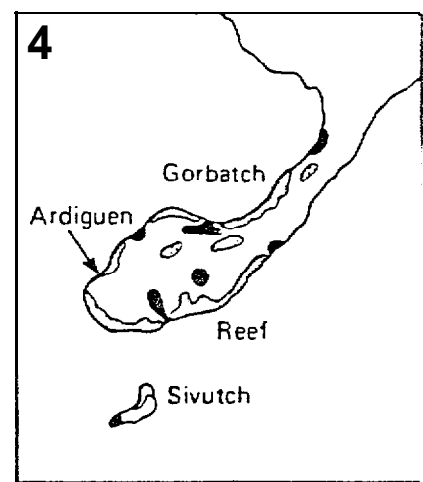
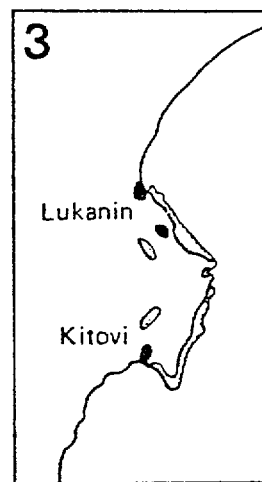
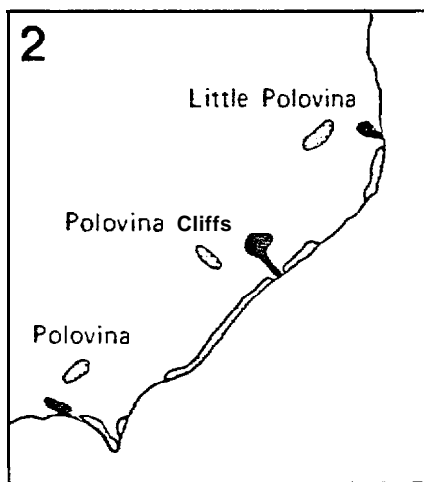
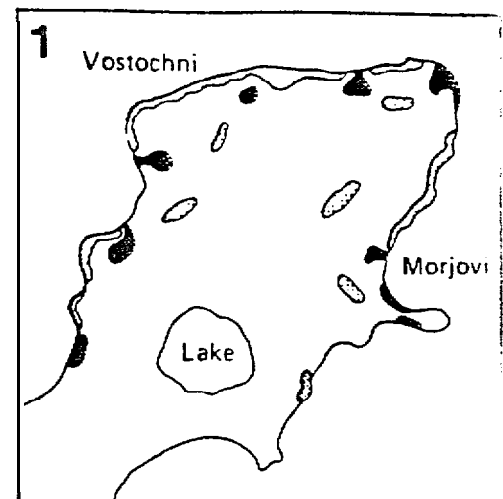
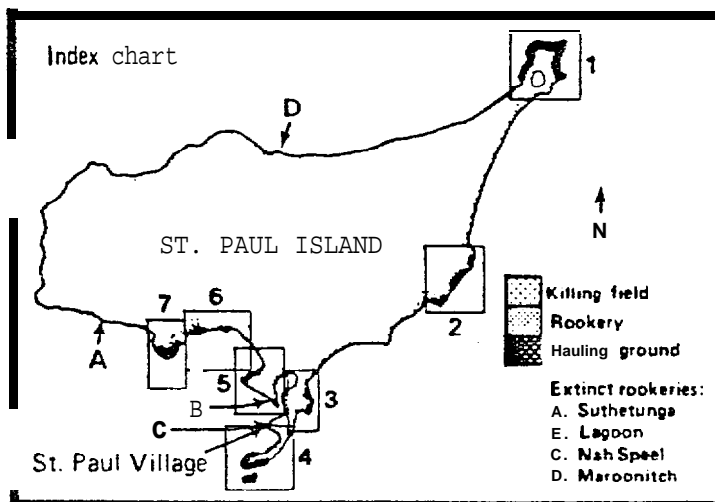


Figure 4-10a. Location of northern fur seal rookeries (present and extinct), hauling grounds, and harvesting areas, St. Paul Island, Alaska from Kozloff (1985).

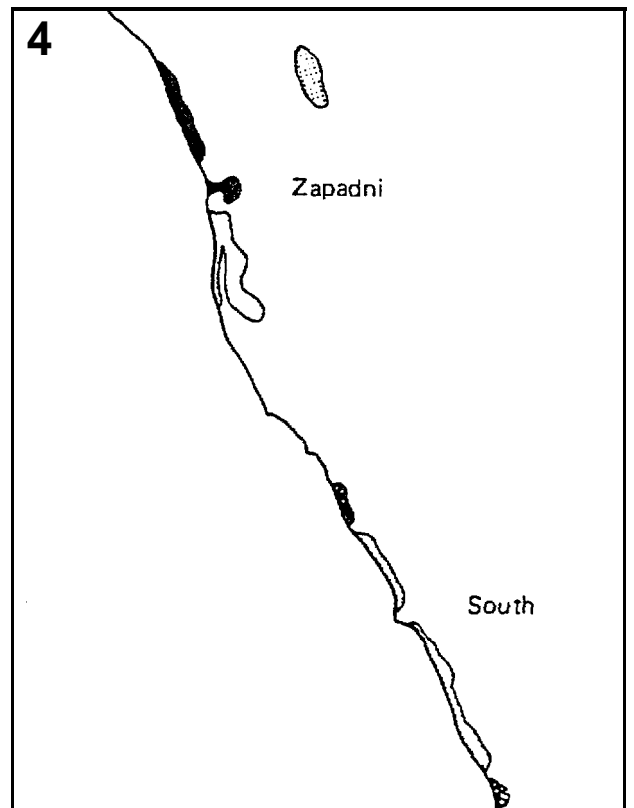
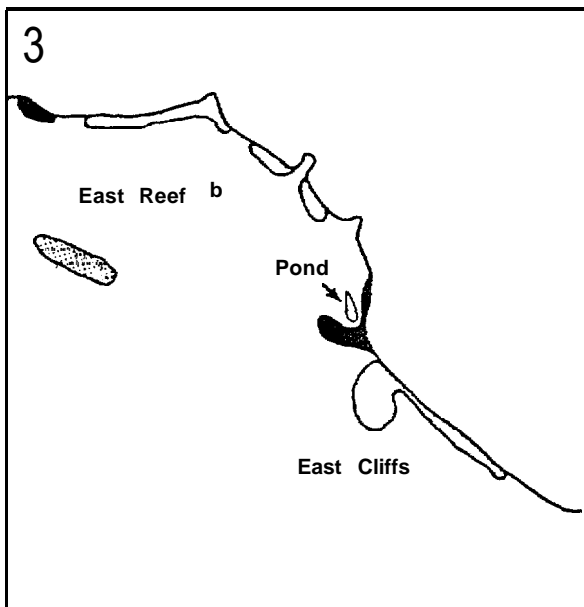
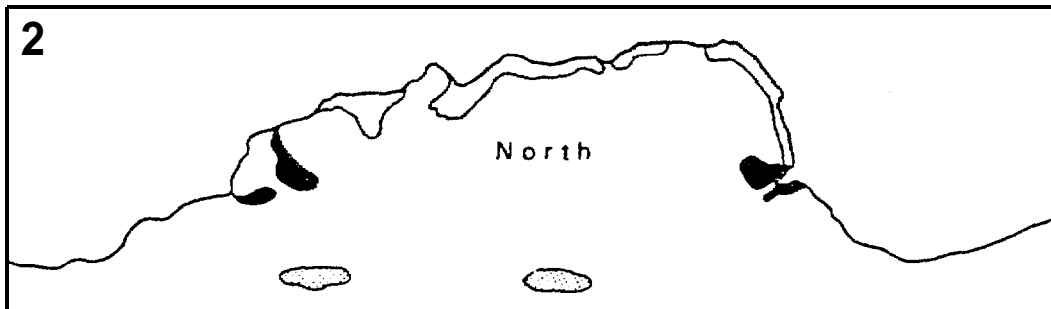
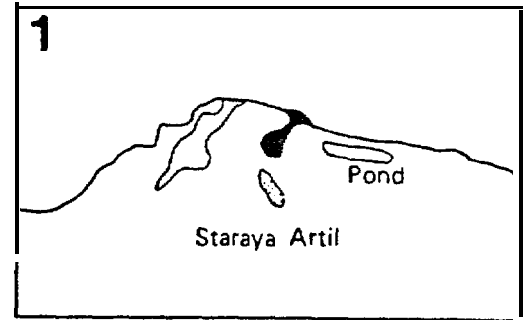
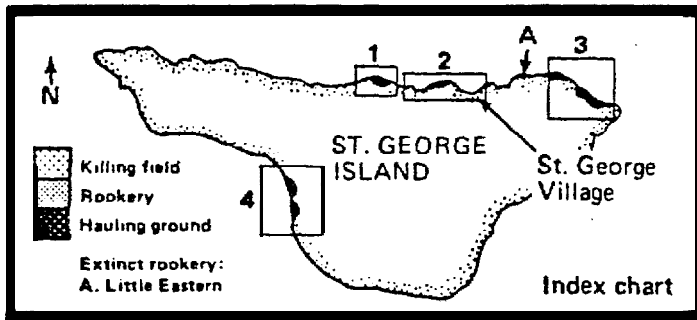


Figure 4-10b. Location of northern fur seal rookeries (present and extinct), hauling grounds, and harvesting areas, St. George Island, Alaska from Kozloff (1985).

Table 4-7. Male Fur Seal Distribution on 21 Existing Rookeries.

Rookery #	Name	# Bulls	% of Total Bulls
	St. Paul Island:	9776	74.3
1	Lukanin	230	1.8
2	Kitovi	466	3.5
3	Reef	1086	8.3
4	Gorbatch	688	5.2
5	A r d i g u e n	64	0.5
6	Morj ovi	739	5.6
7	Vostochni	1791	13.6
8	Little Polovina	260	2.0
9	Polovina	445	3.4
10	Polovina Cliffs	648	4.9
11	Tolstoi	1018	7.7
12	Zapadni Reef	316	2.4
13	Little Zapadni	620	4.7
14	Zapadni	1405	10.7
	St. George Island:	2729	20.7
15	Zapadni	327	2.5
16	South	400	3.0
17	North	1057	8.0
18	East Reef	256	2.0
19	East Cliffs	436	3.3
20	Staraya Artil	253	1.9
	Total both Islands	12505	95.0
21	Sea Lion Rock (Sivutch)	658	5.0
	Total Bulls	13163	100.0

distribution observed for their arrival at the **Pribilofs**, pre-dated by two weeks. Non-pregnant females are assumed to enter in the same distribution (**Bigg**, 1982).

Mature males enter **Unimak** Pass and head for the **Pribilofs** in the same manner, using arrival times from **bull** counts by Peterson (1965) for the temporal distribution. Likewise, immature males enter according to the distribution observed by Gentry (1981). Assumed arrival times in the migration model are shown in Figure 4-9.

Analysis of migration patterns in the Pacific and passage through **Unimak** Pass has shown that younger animals enter at progressively later times (**Bigg**, 1982). In the model, increasing lag times are incorporated with decreasing age, using **Bigg's** estimates. Three year-old females are lagged 4 weeks after adult females. Two year old females lag 3 weeks after 3 year **olds**, and yearlings 3 weeks after that.

All seals older than 3 years are assumed to return to the rookeries each year. The portion of yearlings, 2 year olds and 3 year olds returning was calculated by comparing the percent by age found in the pelagic samples to the percent in the equilibrium model population. The resulting portions of each sex assumed to return are 0.7% for yearlings, 22% for 2 year olds and 98.5% for 3 year **olds** (assumed for both sexes).

Once in the Bering Sea, non-reproductive animals **move** among feeding areas and their respective rookeries according to their probability of being on land on any one day. Gentry and **Holt** (1985) estimated that immature rides spend an average of 19.4% of their time on land. They estimated non-breeding females are on land about 10% of the time. These values are assumed for all ages of non-breeders of each sex.

The portion of bulls holding territories is assumed to be 72.4%, up to a maximum of 12,827 territories. This maximum is based on analysis of territorial and total **bull** counts on **Pribilof** rookeries (**Kozloff**, 1985), showing a linear relationship between the number of territorial bulls and the sum of territorial plus idle **bulls**. There appears to be a maximum of about 12,800 territories on the 21 existing **Pribilof** rookeries, in that territorial bull numbers have not exceeded that number since the early 1900s regardless of total bull numbers. In the model, it is assumed **that** no **more** than 12,927 bulls may hold territories, although it **is** possible that this ceiling, and the number of existing rookeries could change in nature at some time in the future. Idle bulls are treated as other non-reproductive males in their distribution patterns, as are territorial bulls once they leave the rookeries. Territories are apportioned among bulls of various ages according to observations by Johnson (1968, Table 4-8). Territorial males remain on land for an average of 47 days, uniformly distributed between 17 and 77 days (Peterson, 1965). In the model, territorial males have an equal (1/61) probability of leaving their territories each of the 61 days following their 16th day on land. After abandoning **their** territories, bulls behave as other non-breeding males.

Table 4-8. Percent of territories held by bulls of various ages in the model (after Johnson, 1968).

<u>Age</u>	<u>Percent of Territories</u>
7	0.0
8	3.5
9	9.6
10	24.7
11	23.7
12	10.2
13	16.2
14	6.6
15	3.0
16	2.5
17	<u>0 . 0</u>
Total	100.0

Lactating adult females follow well-defined schedules of nursing on land and forage trips to sea. The analysis of Gentry and Holt (1985) provides estimates of **length of visits to land**. The first visit of the female to land for **pupping** and subsequent **nursing** averages 7.4 days, subsequent visits to land for nursing average 2.2 days, with the final visit averaging 3.3 days. In the **model**, visit lengths vary about these means (rounded to the nearest full day) based on distributions provided by **Gentry and Holt**. The durations of visits on land for lactating females in the model are shown in Figure 4-11. During the first visit, pregnant females are assumed to give birth to pups the first day on land. Gentry and **Holt** found that the duration of the feeding trips to sea increased linearly with the age of the pup, and this was incorporated in the model. In the model, their equation for East rookery (duration = $0.04 \times \text{age} + 4$, where age = age of pup in days) was used to calculate a median duration. The actual duration used in each instance was **chosen** at random from the range of median duration ± 1.5 days. Gentry and Holt also found that adult non-reproductive females move on **and off the** rookeries at random; this behavior is reproduced in the model.

Foraging trips to **sea** for all seal types may be directed to any one of 174 foraging areas defined as 1 degree longitude by 1/2 degree latitude grids (Figures 4-12a, b, and c). The choice is made according to a probability distribution **which** is distinct for pregnant and lactating females, non-reproductive females, and males. **The** probability of choosing any one feeding area is equal to the estimated portion of the total population (by type) using that area to feed, i.e. the relative density of feeding animals in the longitude-latitude defined feeding area.

To obtain estimates of relative density, available pelagic fur seal data were analyzed. Pelagic fur seal cruises in the Bering Sea, conducted by the forerunner of the NMML (i.e., the Marine Mammal Biological Laboratory) 1958-1974, collected **over 4000 seals** as well as sightings from over 3600 hours of observation. Resulting data on food habits, age **class** and sighting frequency have been merged to approximate relative densities of feeding fur seals. **The** study area was divided **into** grids of 1/2 degree latitude by 1 degree longitude. Sightings per hour were calculated by

$$S_i = \sum_j n_{ji} / \sum_j t_{ji}$$

where

S_i = sightings per hour in feeding grid i
 n_{ji} = number of seals sighted in grid i on cruise j

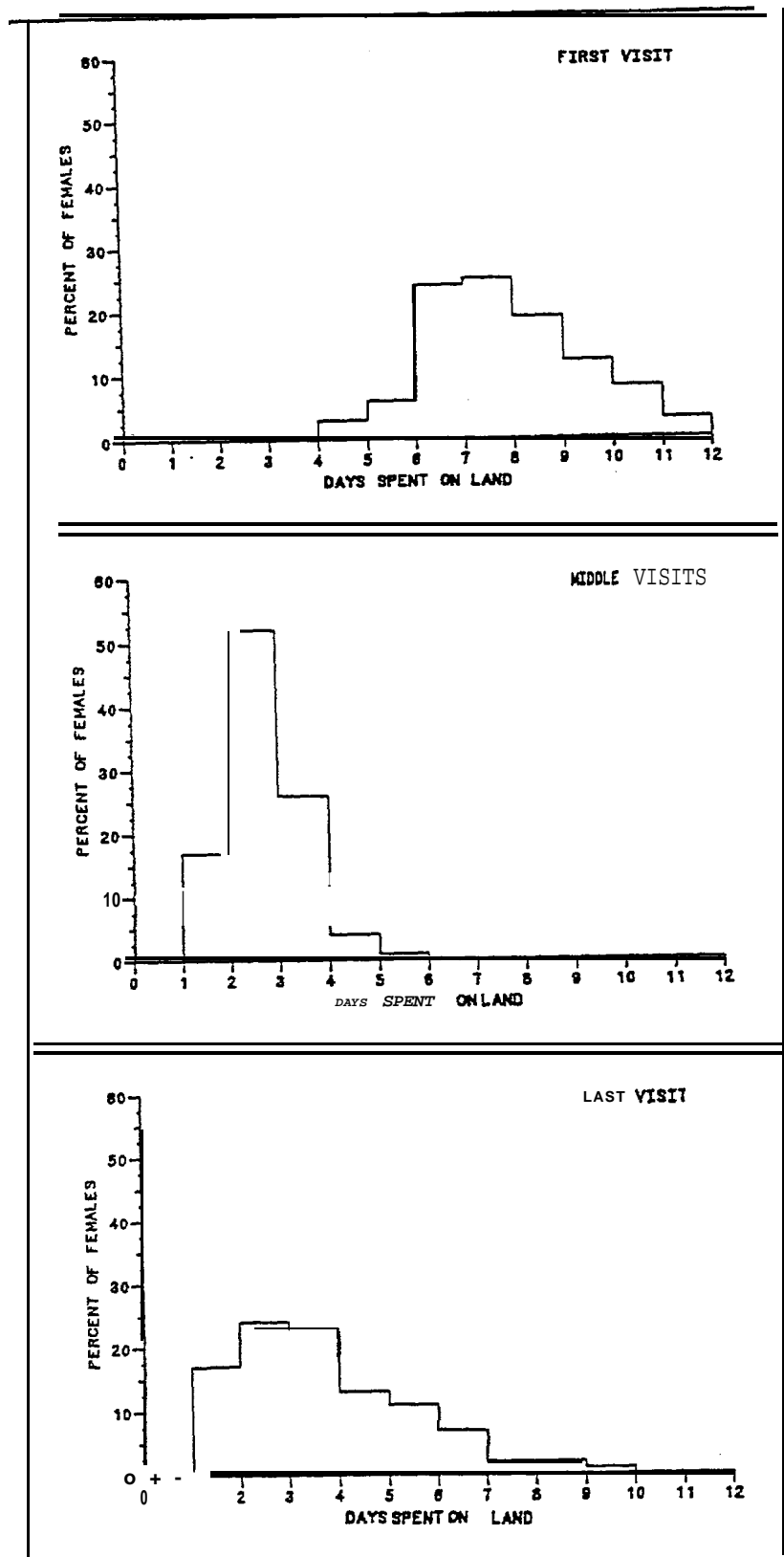


Figure 4-11. Duration of visits to land for lactating females assumed in the model.

Key: Solid =>2%, + = 1-2%, - = 0.5-1%, . =<.5%, empty cell within boundary = 0%

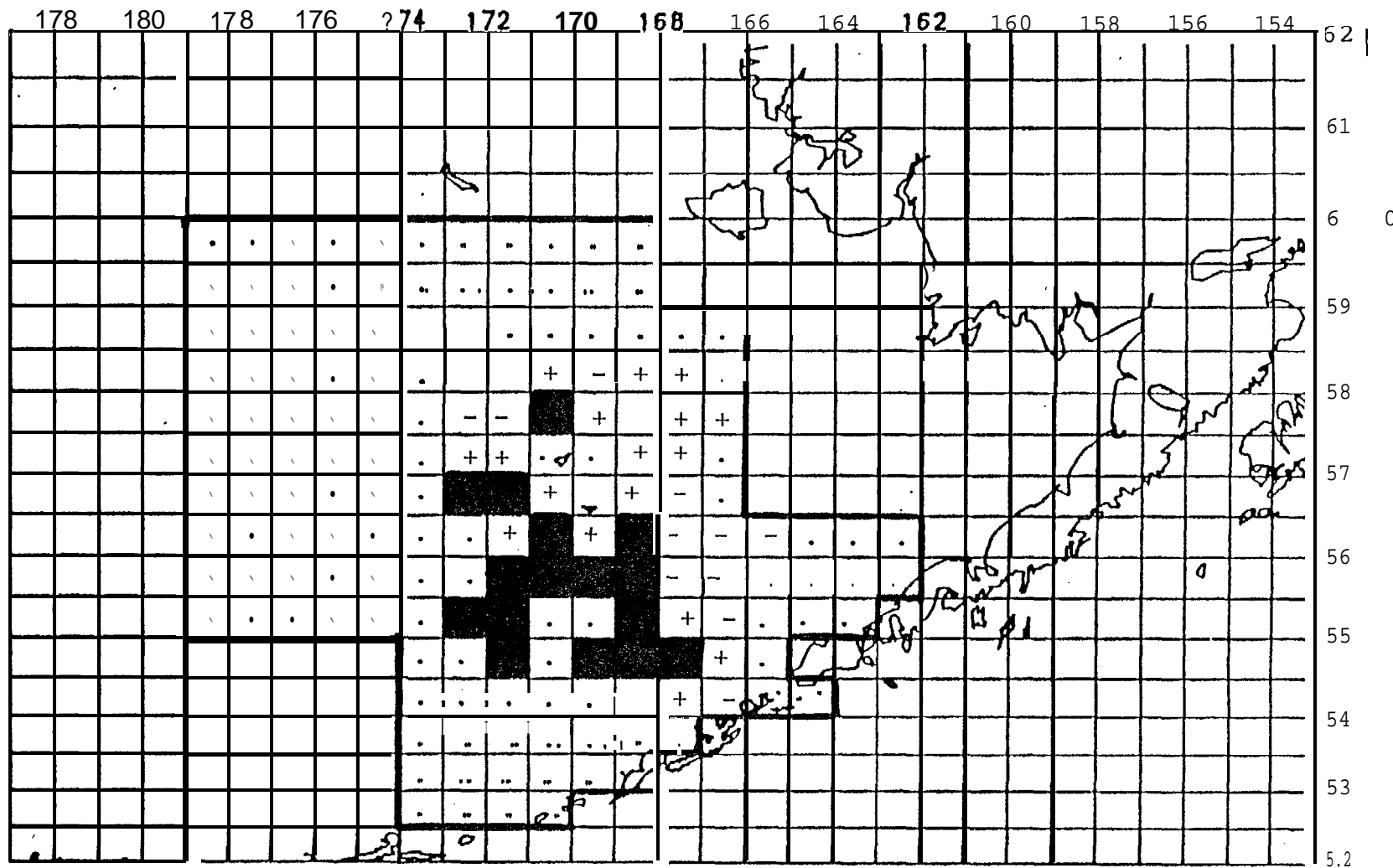


Figure 4-12a. Percent of pregnant or lactating females using individual feeding areas, based on percent of collected seals with partially full stomachs times observed seal densities.

Key: Solid = >2%, + = 1-2%, - = 0.5-1%, . = <.5%, empty cell within boundary = 0%

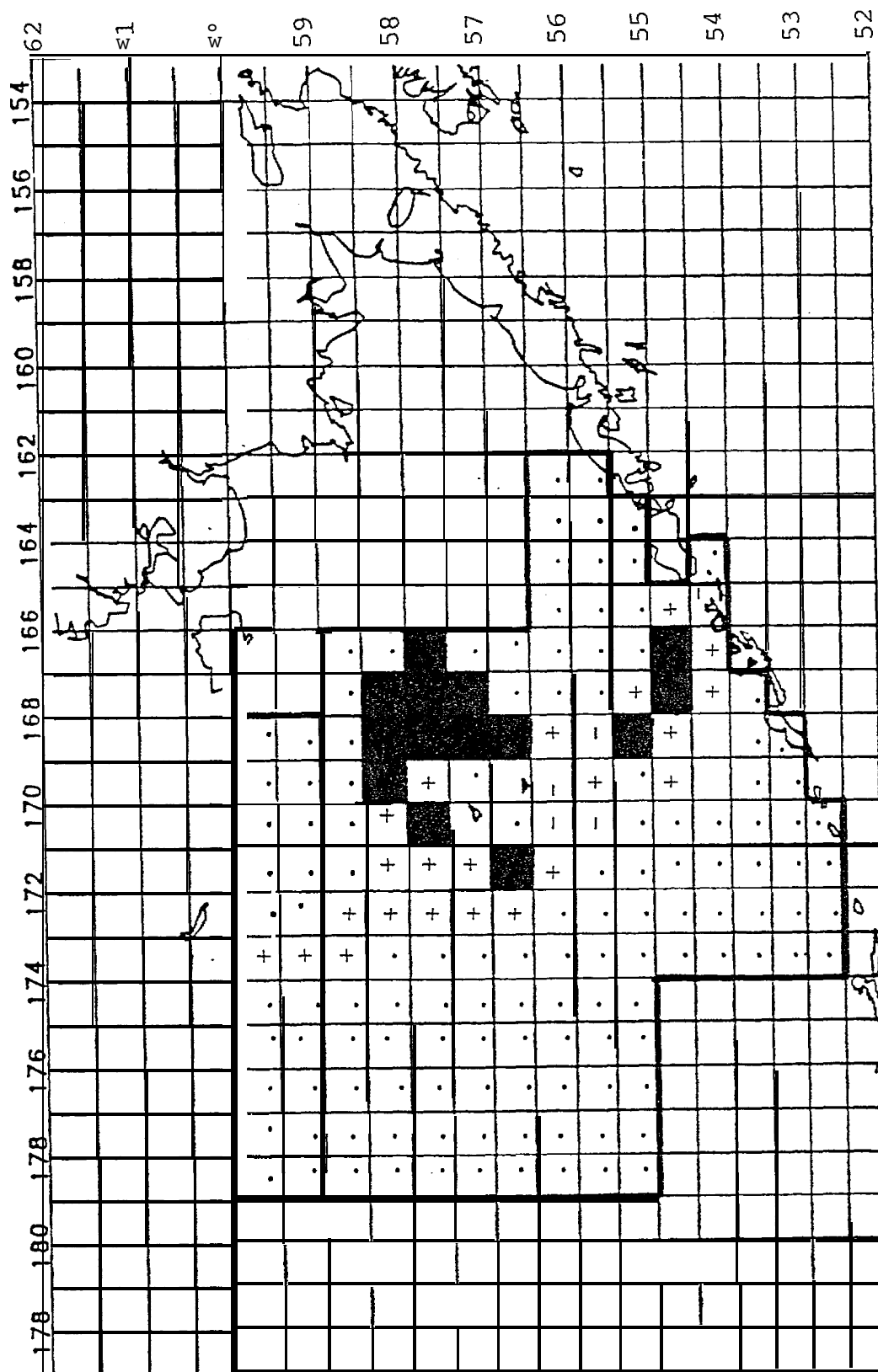


Figure 4-12b. Percent of non-reproductive females of all ages using individual feeding areas, based on percent of collected seals with partially full stomachs times observed seal densities.

Key: Solid =>2%, + = 1-2%, - = 5-1%, . =<.5%, empty cell within boundary = 0%

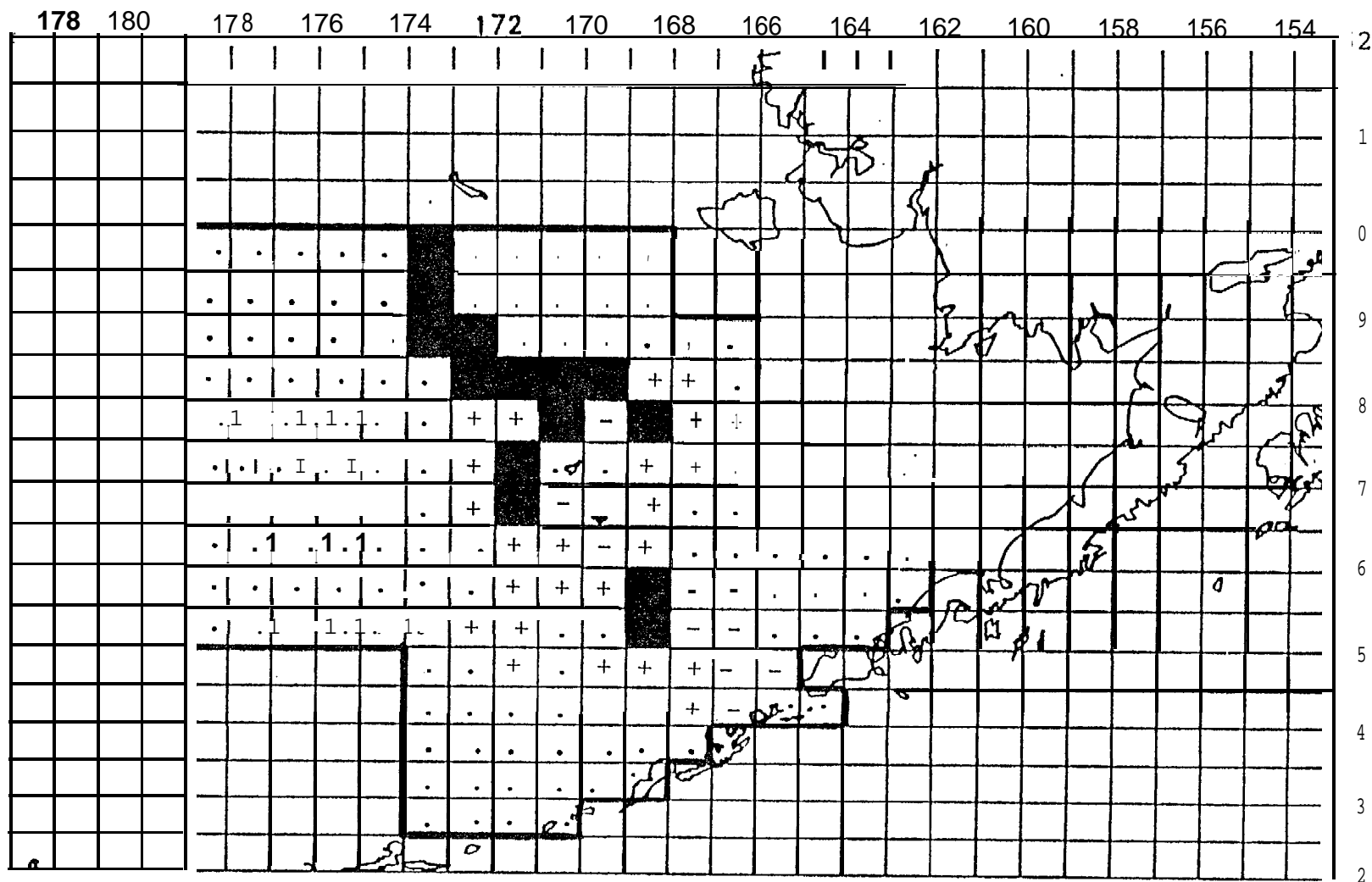


Figure 4-12c. Percent of male seals of all ages using individual feeding areas, based on percent of collected seals with partially full stomachs times observed seal densities.

t_{ji} - number of **observation** hours spent in grid **i** on cruise **j**.

Little observation effort was expended east of 162° W and no fur seal sightings were **made**. Therefore, this region was excluded from consideration and seals are assumed not to travel east of 162° W once in the Bering Sea. Sightings per hour in **all cells** for which observation times were greater than 0.4 hours **were** calculated. To separate feeding areas from areas through which seals are merely passing, percent of stomachs that weighed at least 2.5% of **the body weight** were calculated for each grid. These percents were multiplied by the sightings per hour to determine a Feeding Animal Sighting Index (**FASI**) for each grid. This index forms the core of analysis of relative importance of each area to feeding fur seals.

Age class and sex of animals in each grid were determined as a percentage of the total animals collected. These percentages were multiplied by the FASI (above) to derive an index for each population category. Finally, these indices were **totalled** for each category and the percent in each grid was calculated. The result, which we term the Final Feeding-Density Index (**FFDI**), is an estimate of relative abundance of feeding fur seals for each population category in each grid as a percent of the total number of animals for that category.

Given that animals also occur outside the Study area, we have had to make some extrapolations to areas on the periphery of the sampled areas. These extrapolations **were** performed in two steps. To limit the noise resulting from using percentages of different age and sex categories (low sample size would not be reflected in the index), adjacent cells were pooled into blocks on the periphery so that each block had at least 20 collected seals. The first step in the extrapolation procedure was then **to** distribute the pooled value (**FASI** multiplied by percentage for each category) for a block to the individual **cells** in that block. Each cell was assigned the block value and then included in **the** totals in calculating the **FFDI**. For example, a hypothetical block might contain 3 cells. The data in the cells were pooled, the FASI determined and multiplied by the percentage of each age and sex category. **This** index was assigned to each of the 3 cells. When the FFDI was calculated, the values in each cell were added to all other values for that category to derive the denominator for the percentage in each cell. In this manner, all cells with collection data were assigned an **FFDI**.

The second extrapolation step was required to **determine** indexes for areas that had no collection data and very few sighting **data**. From **Kajimura (1980a,b,c)**, who summarized data from opportunistic sightings, and Townsend (1899), who summarized historical pelagic sealing data, there appear **to** be fur seals in areas outside **the** areas in which NMFS **collected** seals. To determine **the** portion of animals outside

the core and block areas, we first used sighting data. From these data we drew broad borders for this outer zone (e.g. Figure 4-12a). This outer zone consists of 100 cells. All cells in the **outer** zone with sighting data (15) were pooled (total seals/total hours) to arrive at an average sighting rate for the outer zone. The same was done for the core and block areas. This sighting rate was multiplied by the number of **cells** to derive a sighting index for both the core and block areas and the outer zone. From this analysis, the density of seals in the outer zone relative to **the** core plus block areas was determined. Eleven percent (11%) of the seals were calculated to be in the **outer** zone. Thus, the FFDI for the core and blocks was reduced to 89%, and the other 11% were evenly distributed throughout the outer zone (100 cells).

Age and sex categories were pooled to increase **sample** size. Inspection of the data showed that different age classes of males have small sample sizes. A matrix of correlations between the **number** of collected seals in each cell for different age and sex categories was run. From this analysis, locations of males of all age classes had more **in** common with each other than with females of any age. Thus males of all ages form one category for the FFDI (Figure 4-12c). Pregnant or lactating mature (4 or **more** years old) females form another category (Figure 4-12a) and non-reproducing females (all ages; Figure 4-12b) form the third category. Yearlings were not added to any category.

Although many age classes are pooled for the distribution figures, age classes are considered separately in the **model** because of differences in: 1) **the** arrival and departure times of different age groups, 2) the proportion on land at different times, and 3) the proportion entering the Bering Sea. Data on yearlings were not considered since the sample sizes were insignificant. The distribution of the small portion of these animals that enter the Bering Sea late in the season is assumed **to** be the same as for the other immature animals for their respective sexes.

The assumptions made in the above analysis include:

- The core, blocks and outer zone represent 100% of the fur seals **in** the Bering Sea.
- The **full** stomach cutoff of 2.5% of the body weight **is** indicative of whether a seal is feeding in or simply traveling through that area.
- Monthly changes in distribution do not confound the data, and are offset by the increased sample sizes gained through pooling.
- Sighting indexes of animals are not greatly different from feeding indexes. That is, the calculations needed to derive the **1-11%** of the animals in the outer zone reflect feeding animals, even though they are based on sightings only. (No

collections were made in the outer zone.)

- Changes in visibility distances and other sighting biases are inconsequential.

It is not known whether individual fur seals exploit many or just a few feeding areas during a summer season. Depth-time recordings of lactating female activities **by** Gentry (1984) and Gentry et al (1985) suggest that they exploit primarily **one** feeding location. However, observations **by** Gentry (1981) suggest that non-reproductive seals (specifically immature males) may not be so focused in their behavior. In the model, lactating females always return to the same feeding area throughout the summer, whereas all other seal types choose at random **among** 5 possible feeding **areas** per individual. This latter assumption allows some remixing of the non-reproductive population. The number of feeding areas visited by a single individual does not affect the overall average distribution of seals in the model, only that of one individual, since, on average, the same number of seals visit any one feeding area at a given time. In the **model**, individual seals are assigned feeding areas at initialization according to the probability distributions in Figure 4-12a, b, and c.

When in transit to and from feeding areas, seals are assumed to swim at 200 km/day (about 4.5 knots). Radio tagging of lactating females by **Loughlin** et al (1985) showed that females swim 3-4 knots on **the** way to feeding areas and 5-7 knots upon returning. These velocities are similar to those **observed** by Lavigne et al (1982) for gray seals. The farthest feeding areas are 2 days swimming distance from the rookeries. However, most seals feed within a day's swimming distance of the **Pribilofs**. A random component of plus or minus 10% is induced on both velocity and direction when seals are moving.

While seals are feeding **at** sea, they move at an assumed velocity of 20 km/day, in a randomly chosen direction **each** time step, **within** the feeding area they have selected. Seals are not allowed to move onto land while feeding at sea.

In the model, seals leave the Bering Sea according to probability distributions based on the analyses of Gentry (1981) on immature males and Gentry and Holt (1985) on lactating females. Animals

other than adult females and pups are assumed to depart according to **the** distribution for immature males. Lactating females and **PUPS** **leave when** the pups are weaned (age 111-128 days), and non-lactating adult females are assumed to leave at this time as well (Gentry and **Holt**, 1985). Figure 4-13 shows the distribution of departure times from the **Pribilof** Islands assumed in the model. All seals other than pups are assumed to swim at 40 km/day \pm 10% while traveling toward **Unimak** Pass during their departure. Thus, transit time is about 2 weeks. Pups are thought to take longer to cross the Bering **Sea**, on the order of one **month** (**Kajimura**, 1979). **Therefore**, they are assumed to swim at 20 km/day \pm 10%.

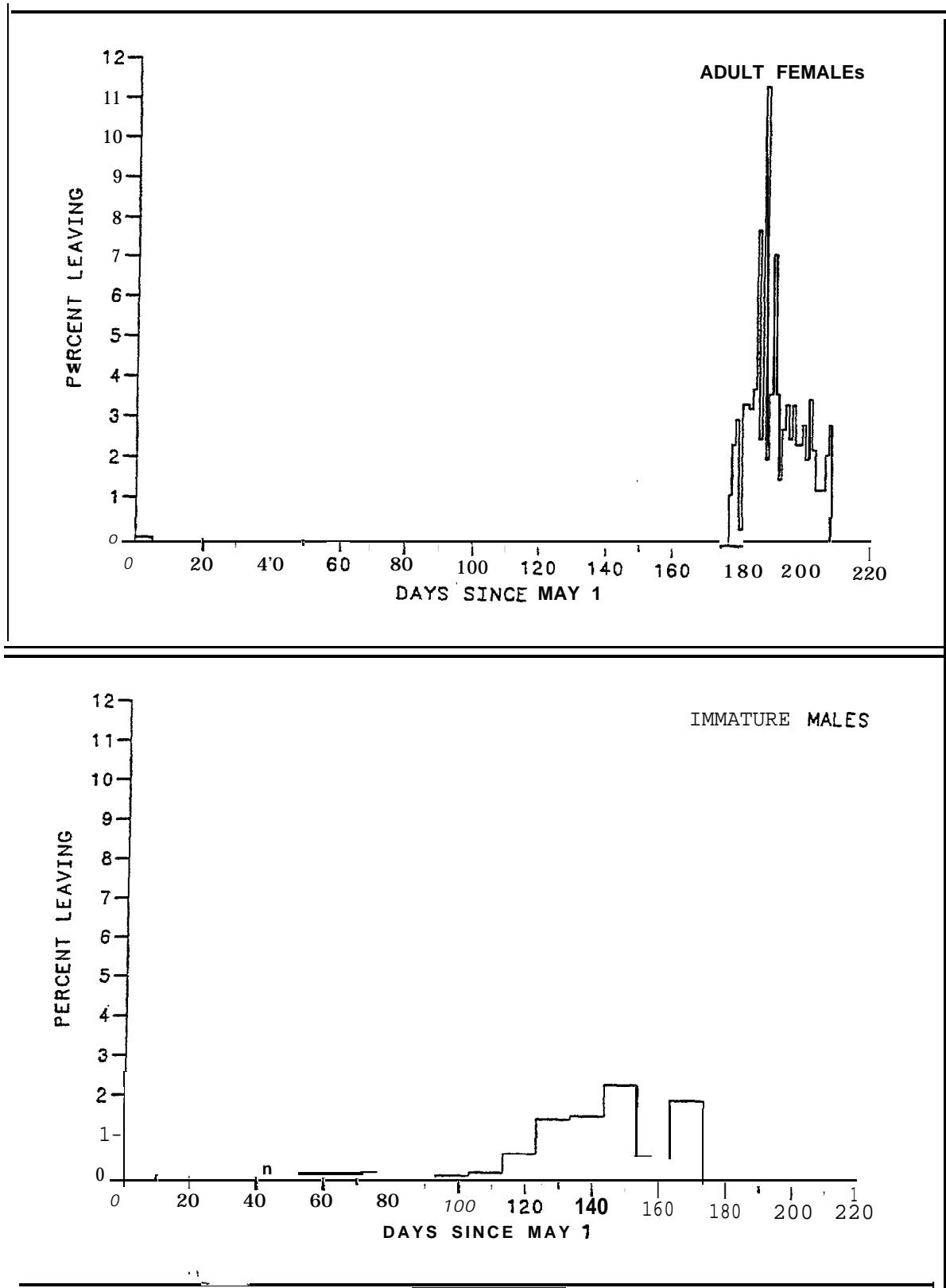


Figure 4-13. Distribution of departure times for the Pribilof rookeries by seal type assumed in the migration model. Seals swim to Unimak Pass following departure. The distribution for lactating females is based on the analysis of Gentry and Holt (1985), and that for immature males is based on Gentry (1981).

Comparison of Modeled **and Observed Fur Seal** Distributions

Movements are simulated at a time step on the order of fractions of days **to** days, since **many** movements are redirected within one or two days (lactating female **visits** to land, for example). Figures 4-14a and b show simulated numbers **hauled** out on land. These agree with land count data in timing and relative numbers (Bartholomew and Heel, 1953; Peterson, 1965).

Snapshots of the modeled distributions of fur seals are shown at 20 day **intervals** in Figures 4-15a through l. **These** figures represent a random sample of 400 seals from the entire population. **Only** those seals inside the Bering Sea **are** plotted. The **bulls** appear first (Figure 4-15a), with females appearing about a **month** later (Figure 4-15c). From early July (Figure 4-15d) through the end of **October** (Figure 4-15h), summer feeding activities in the Bering Sea govern the distributions. Exodus south through **Unimak** Pass begins at the end of October (Figure 4-15i and j) and **is** nearly complete by mid-December (Figure 4-15l).

Modeled behavior patterns of a sample of individual seals are shown in Figure 4-16a through f. Figures 4-16a and b show summer tracks for an immature male and female respectively. Figure 4-16c shows the feeding patterns for a **non-reproductive** mature female. Movements of a mature, non-territorial bull are shown in Figure 4-16d. Figures 4-16e and f show the relatively focused feeding activity of lactating females, as **well** as their pathways in and out of the Bering Sea.

Since individual seals visit only a **small** number of feeding areas, a large **enough** number of seal "points" must be used so that the simulated distribution matches the **observed**. The model population at **equilibrium** has 52 different **age/sex** classes on January 1 consisting of males, pregnant females and non-breeding females of various ages (Table 4-2). The migration model was initialized with a range of replicate numbers of these 52 seal point types. Thus each seal point represents the total number of seals of that type divided by the number of replicate points. To measure fit of the modeled distribution to the observed, a **chi-squared** (χ^2) test was performed where

$$\chi^2 = \sum_i \frac{(\text{FFDI}_i - M_i)^2}{\text{FFDI}_i}$$

FFDI_i is the "Final Feeding Density Index" for grid cell i, the **observed** percent of the population utilizing a given grid cell for feeding as described in the previous section. M_i is the simulated average percent of the population using grid cell i. As shown in Table 4-9, at **least** 40 replicate points are required to adequately reproduce **the observed** feeding

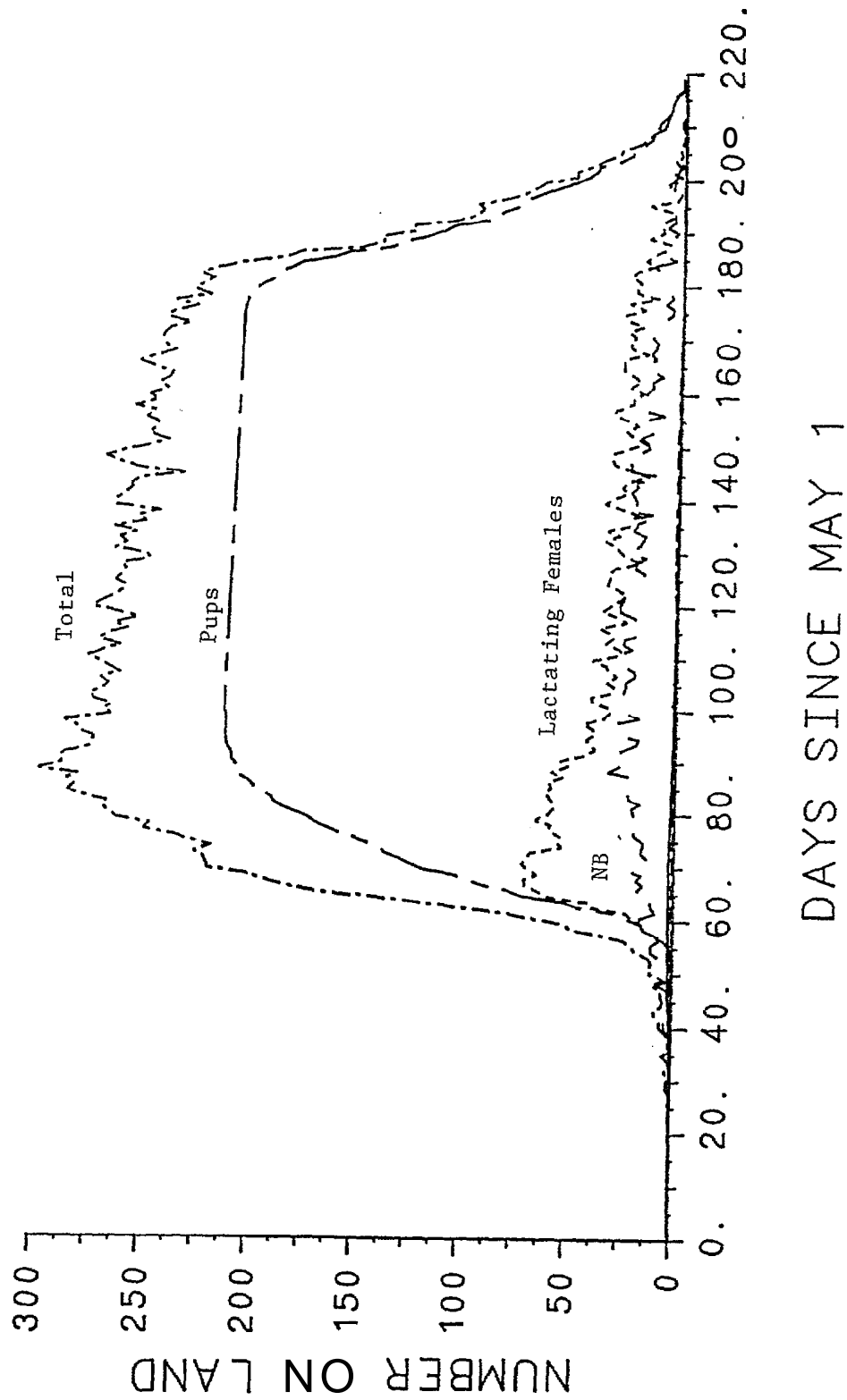


Figure 4-14a. Numbers of seals on land (in thousands) in the model population NB = non-breeders).

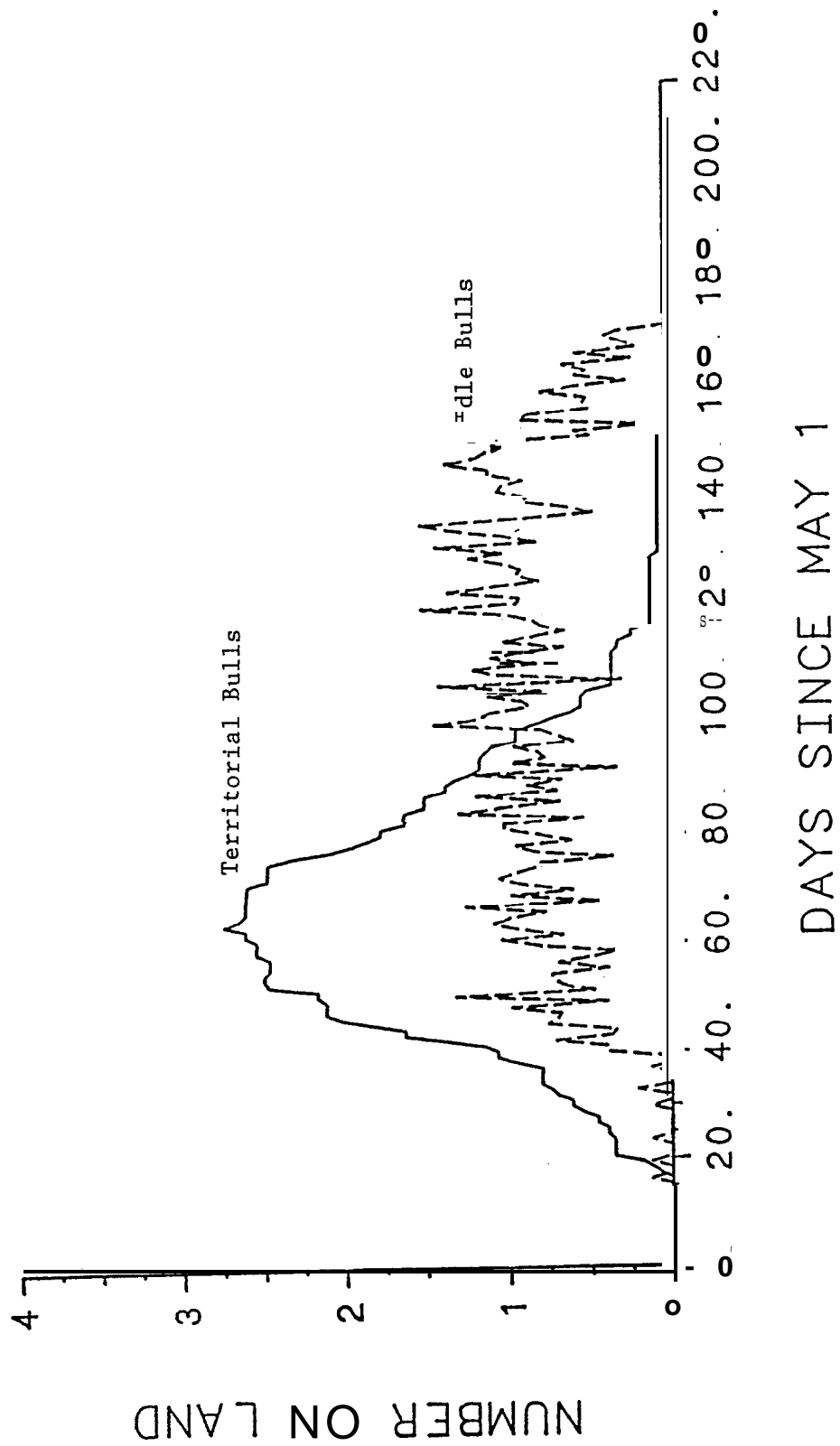


Figure 4-14b. Numbers of bulls on land (in thousands) in the model population.

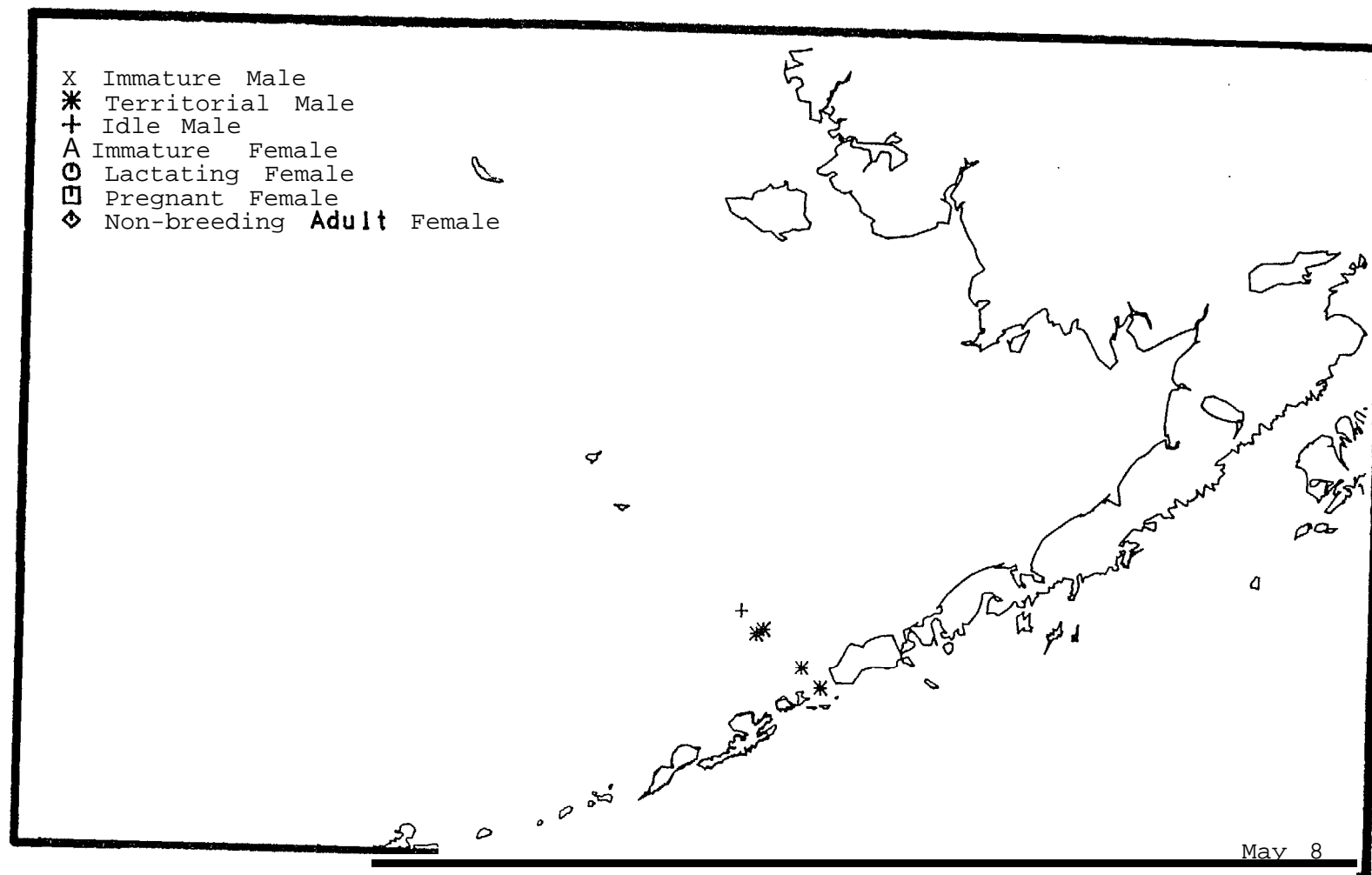


Figure 4-15a, Sample distribution of simulated fur seals in the Bering Sea on May 8 (Julian day 128) .

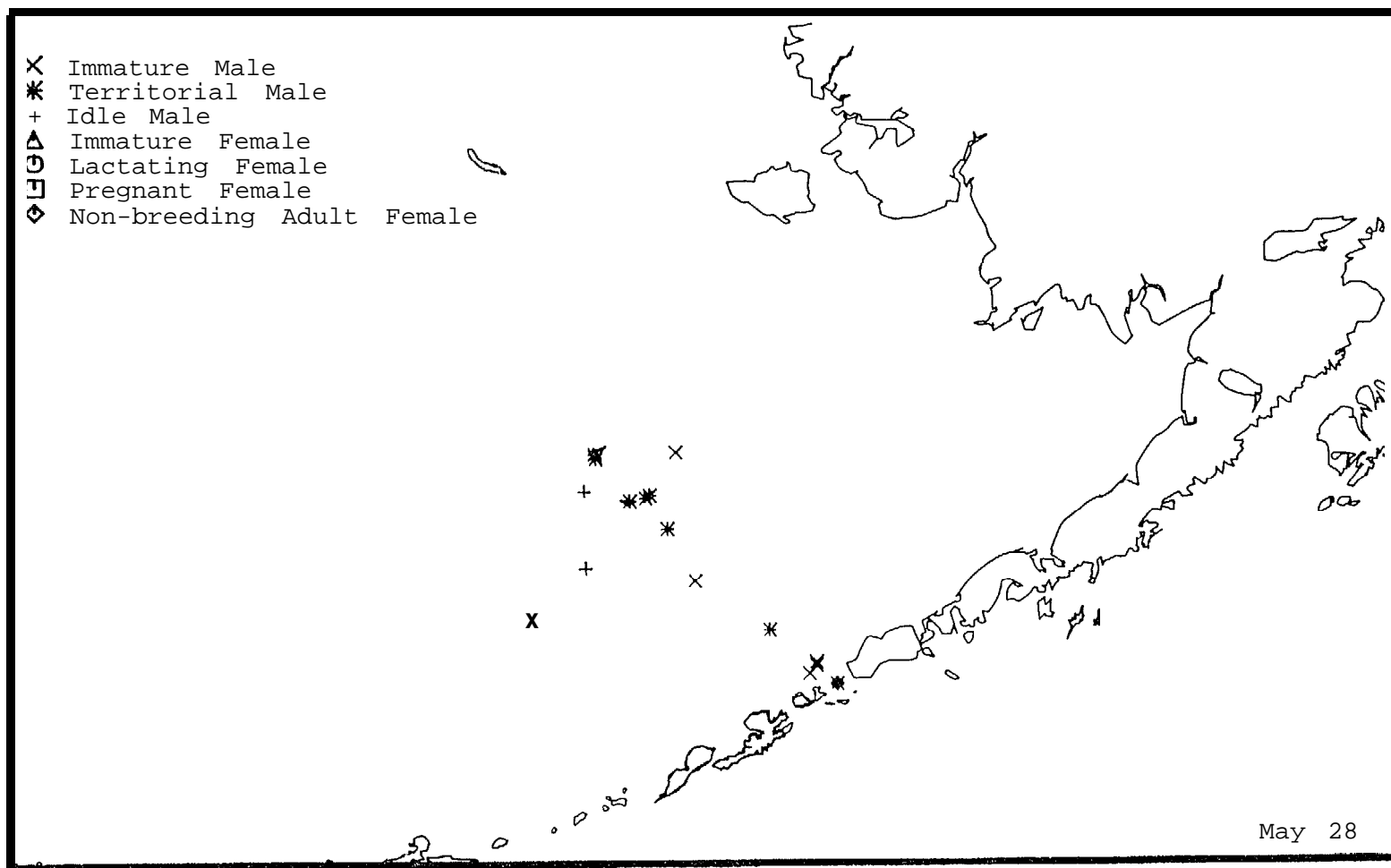


Figure 4-15b. Sample distribution of simulated fur seals in the Bering Sea on May 28 (Julian day 148) .

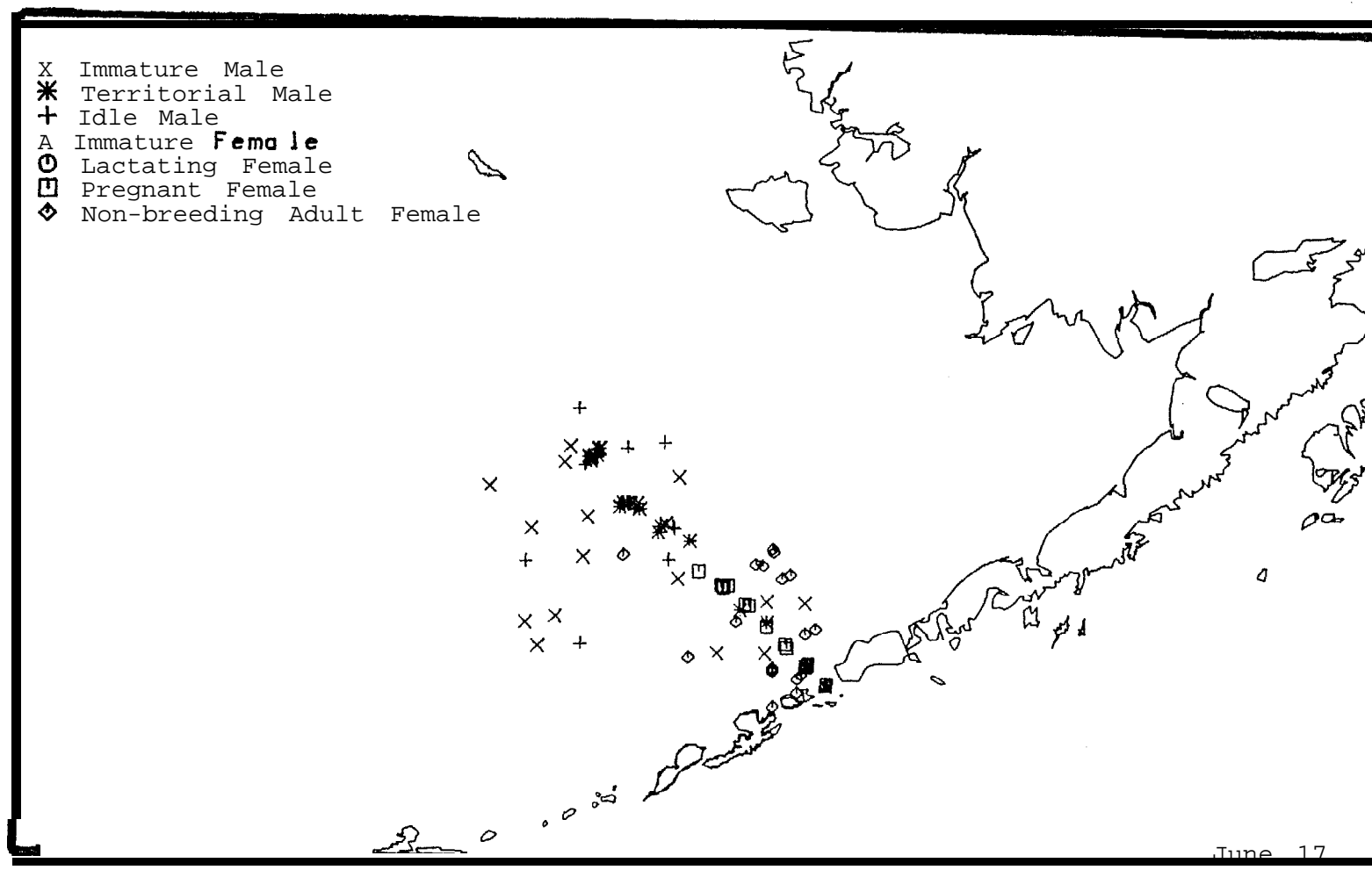


Figure 4-15c. Sample distribution of simulated fur seals in the Bering Sea on June 17 (Julian day 168).

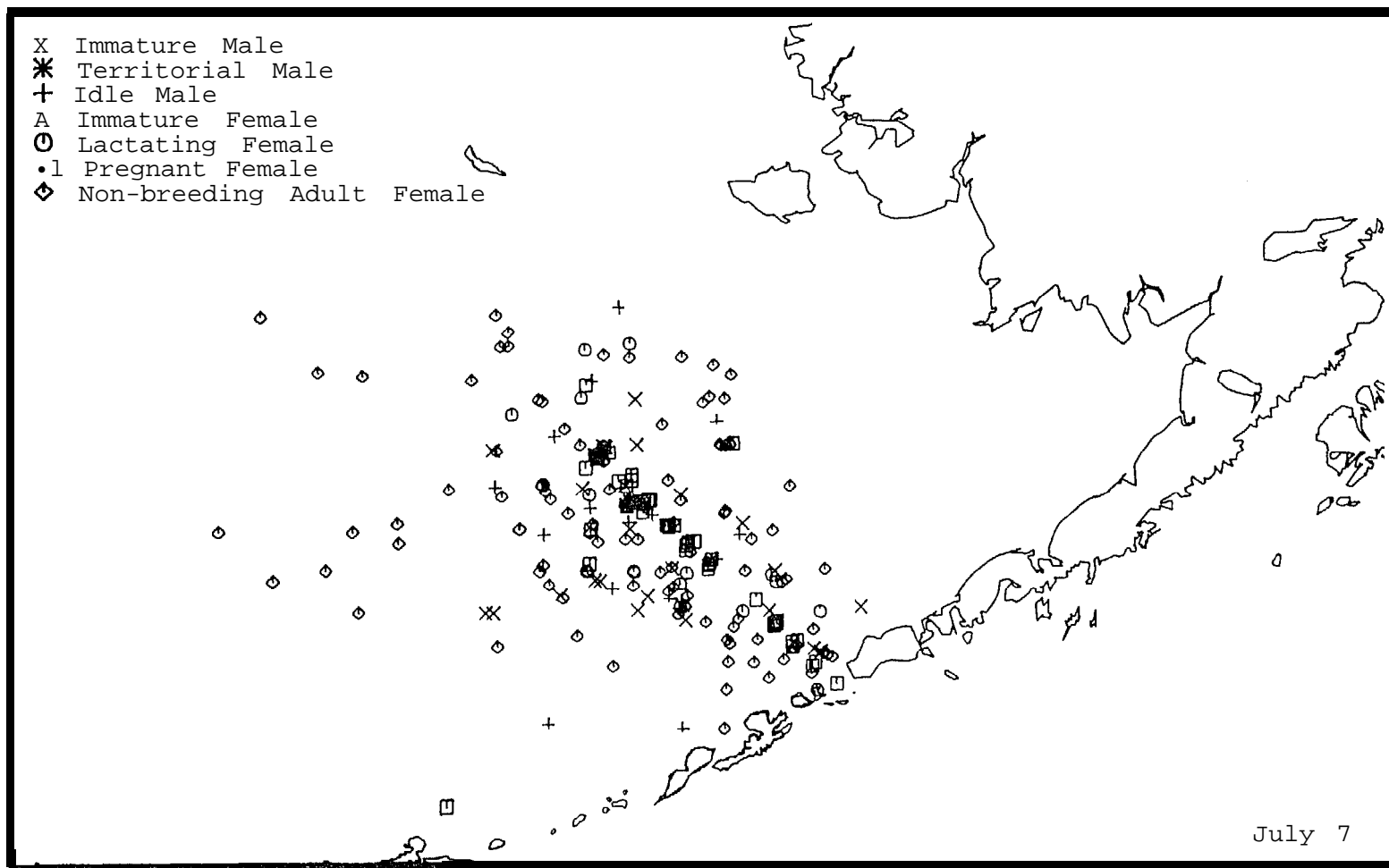


Figure 4-15d. Sample distribution of simulated fur seals in the Bering Sea
On July 7 (Julian day 188) .

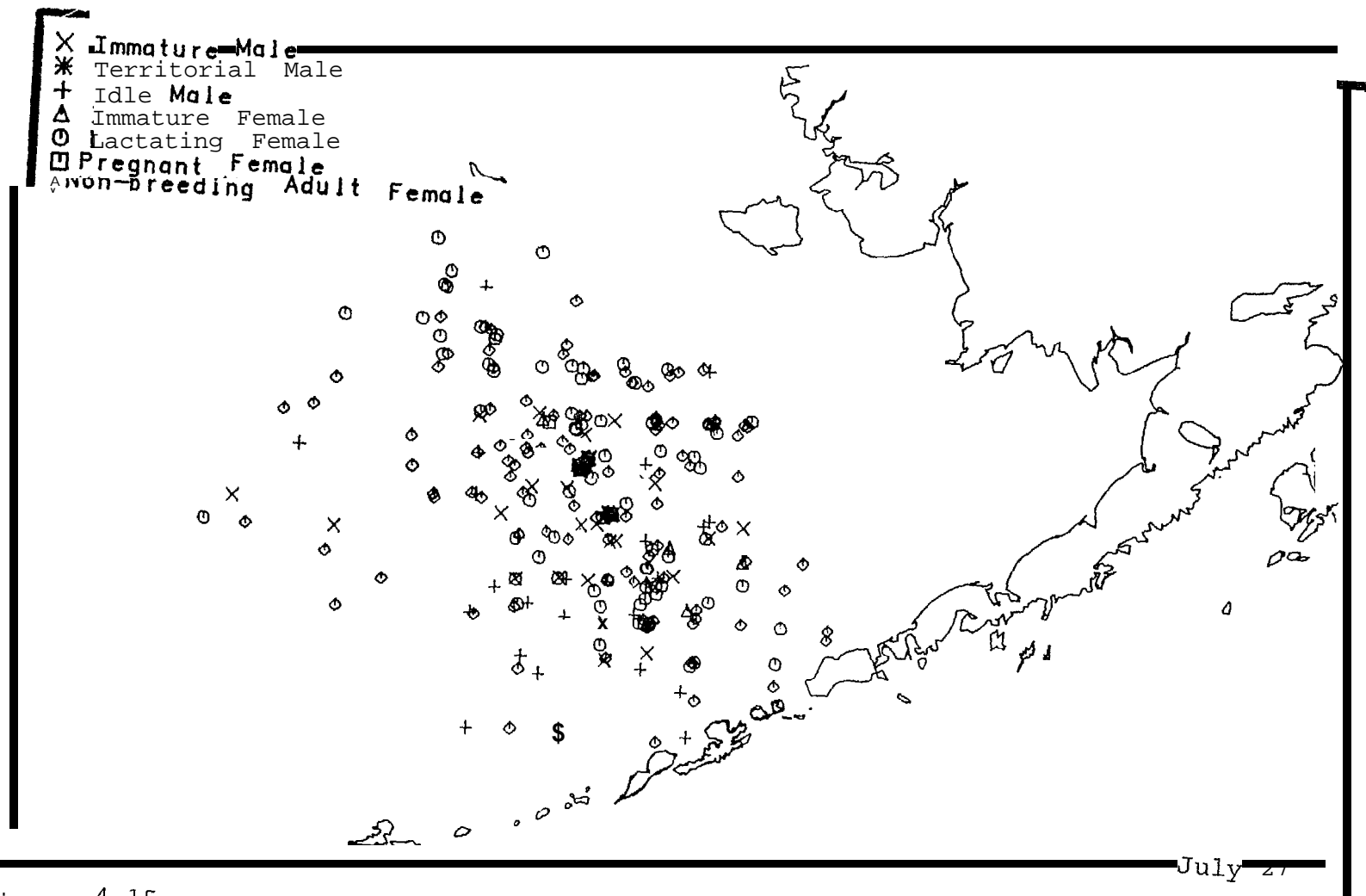


Figure 4-15e.

Sample distribution of simulated fur seals in the Bering Sea on July 27 (Julian day 208).

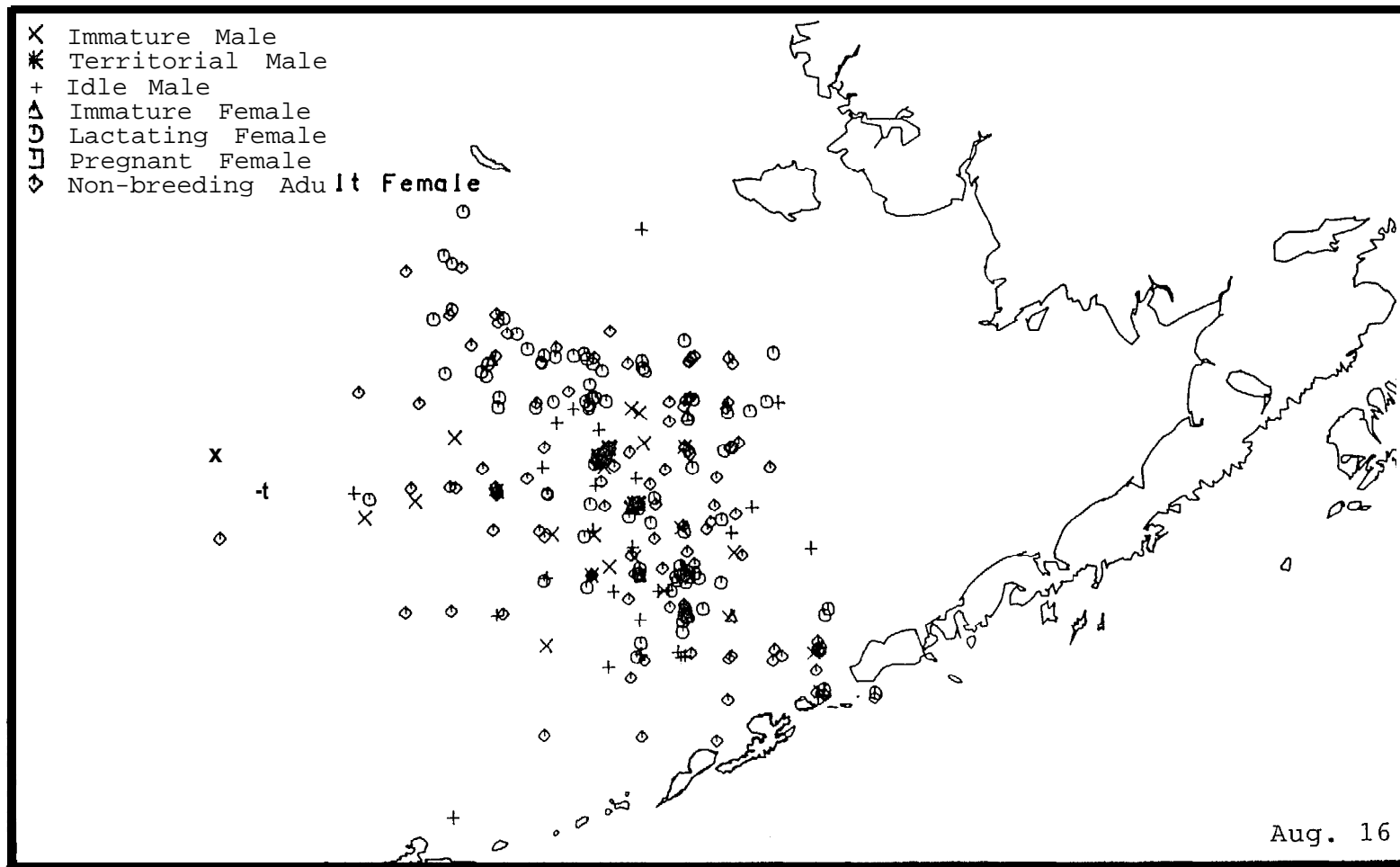


Figure 4-15f. Sample distribution of simulated fur seals in the Bering Sea on August 16 (Julian day 228) .

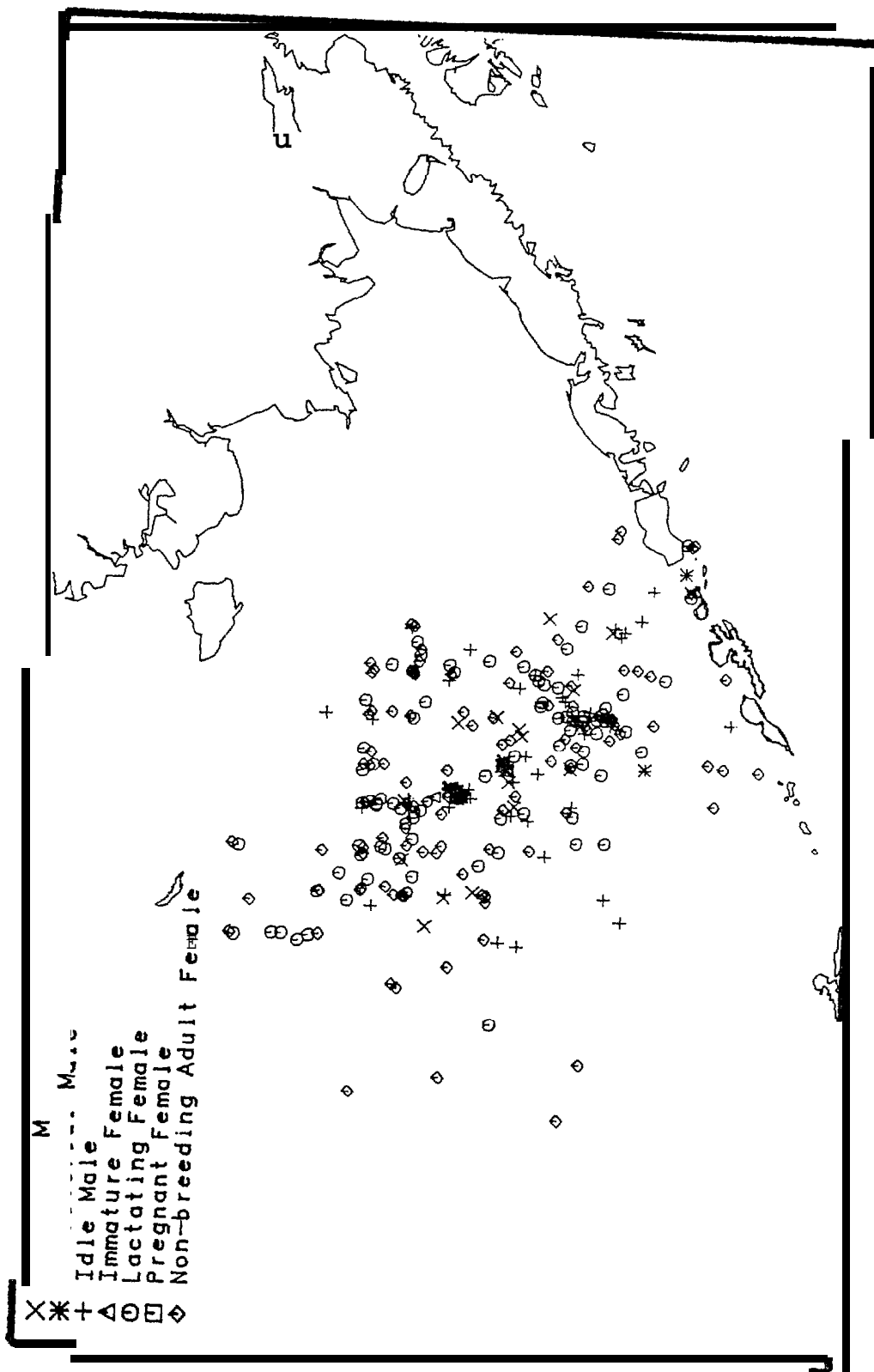


Figure 4-15g. Sample distribution of simulated fur seals in the Bering Sea on September 5 (Julian day 248).

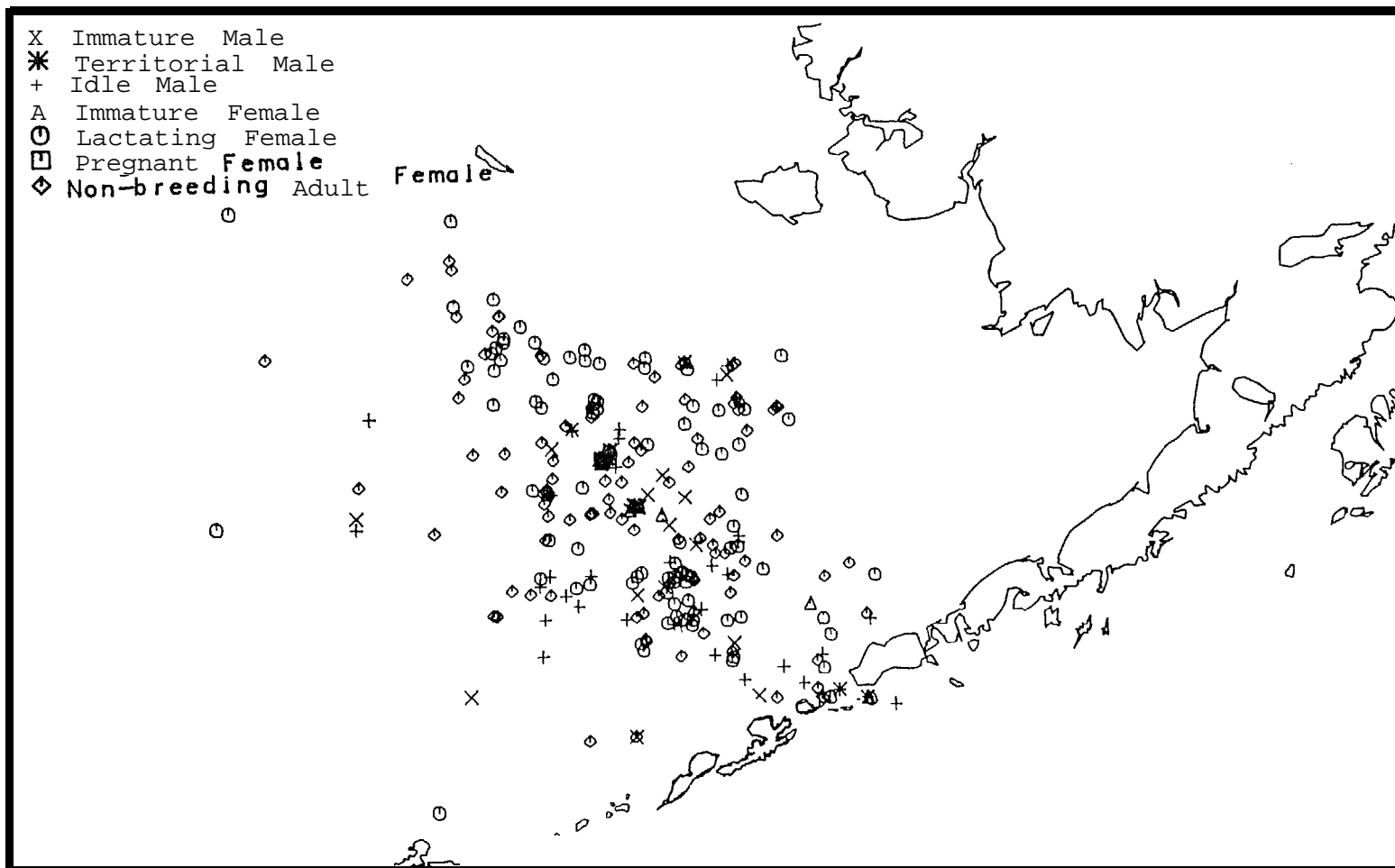


Figure 4-15h. Sample distribution of simulated fur seals in the Bering Sea on September 25 (Julian day 268) .

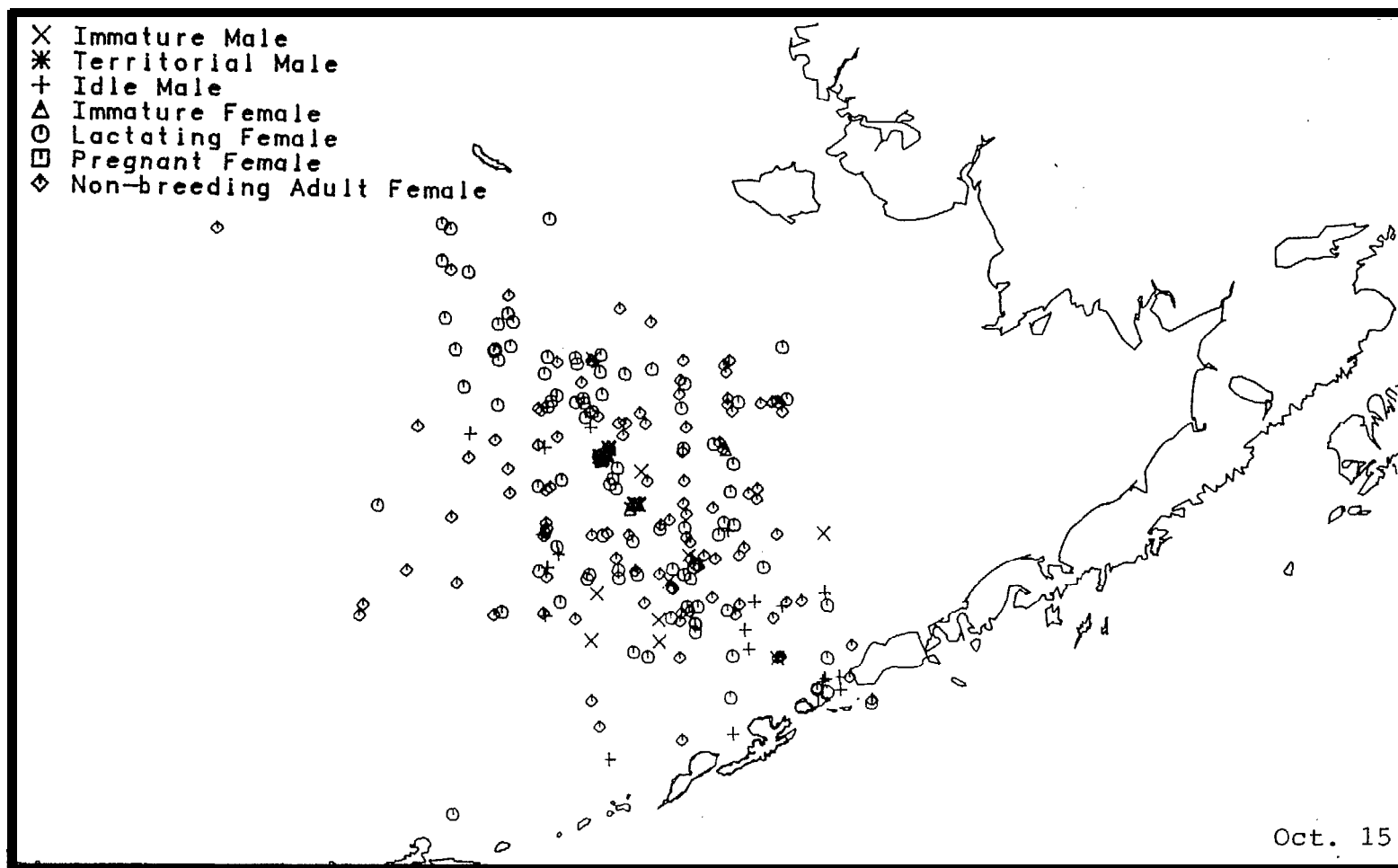


Figure 4-15i. Sample distribution of simulated fur seals in the Bering Sea on October 15 (Julian day 288) .

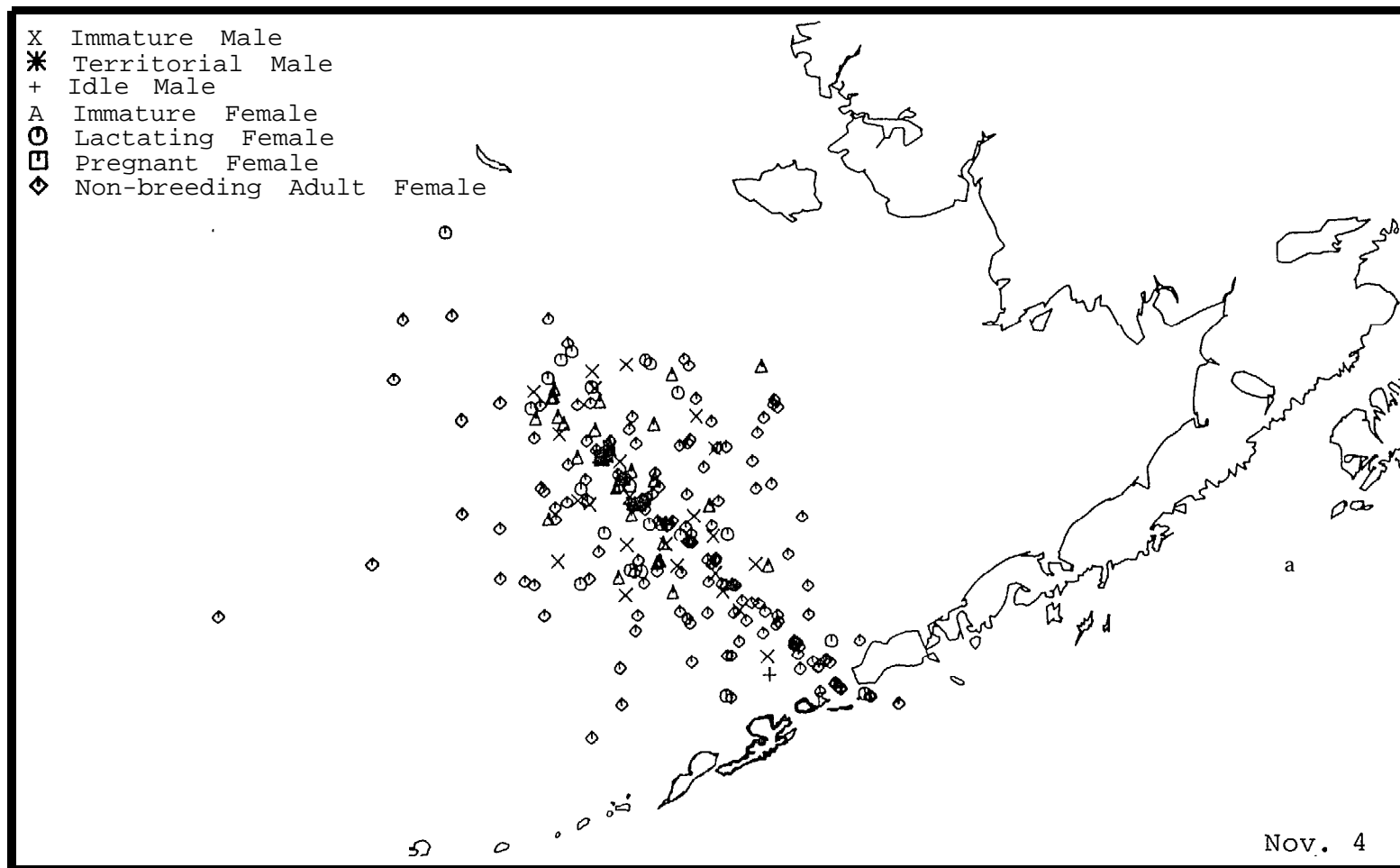


Figure 4-15j. Sample distribution of simulated fur seals in the Bering Sea on November 4 (Julian day 308) .

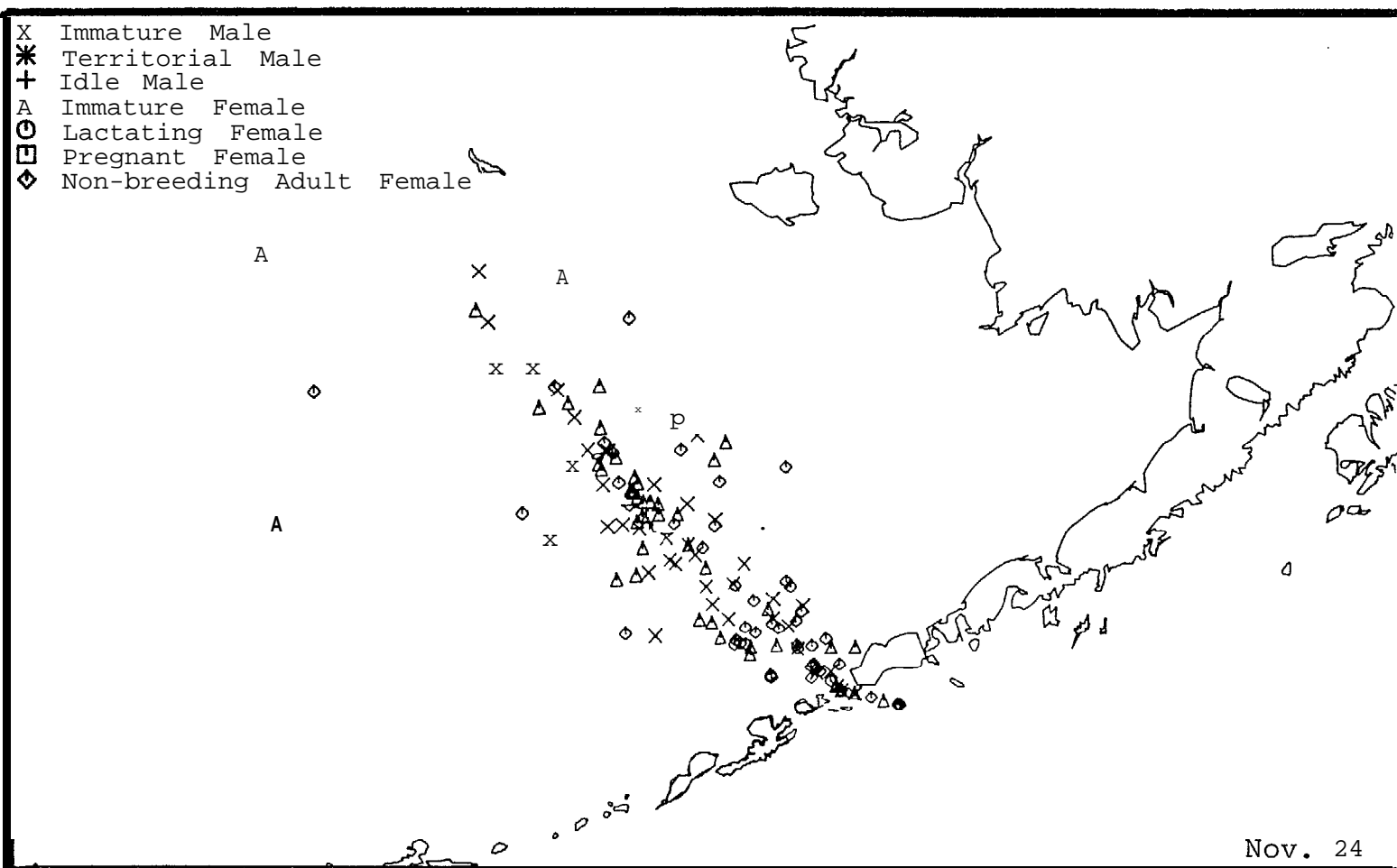


Figure 4-15k. Sample distribution of simulated fur seals in the Bering Sea
On November 24 (Julian day 328) .

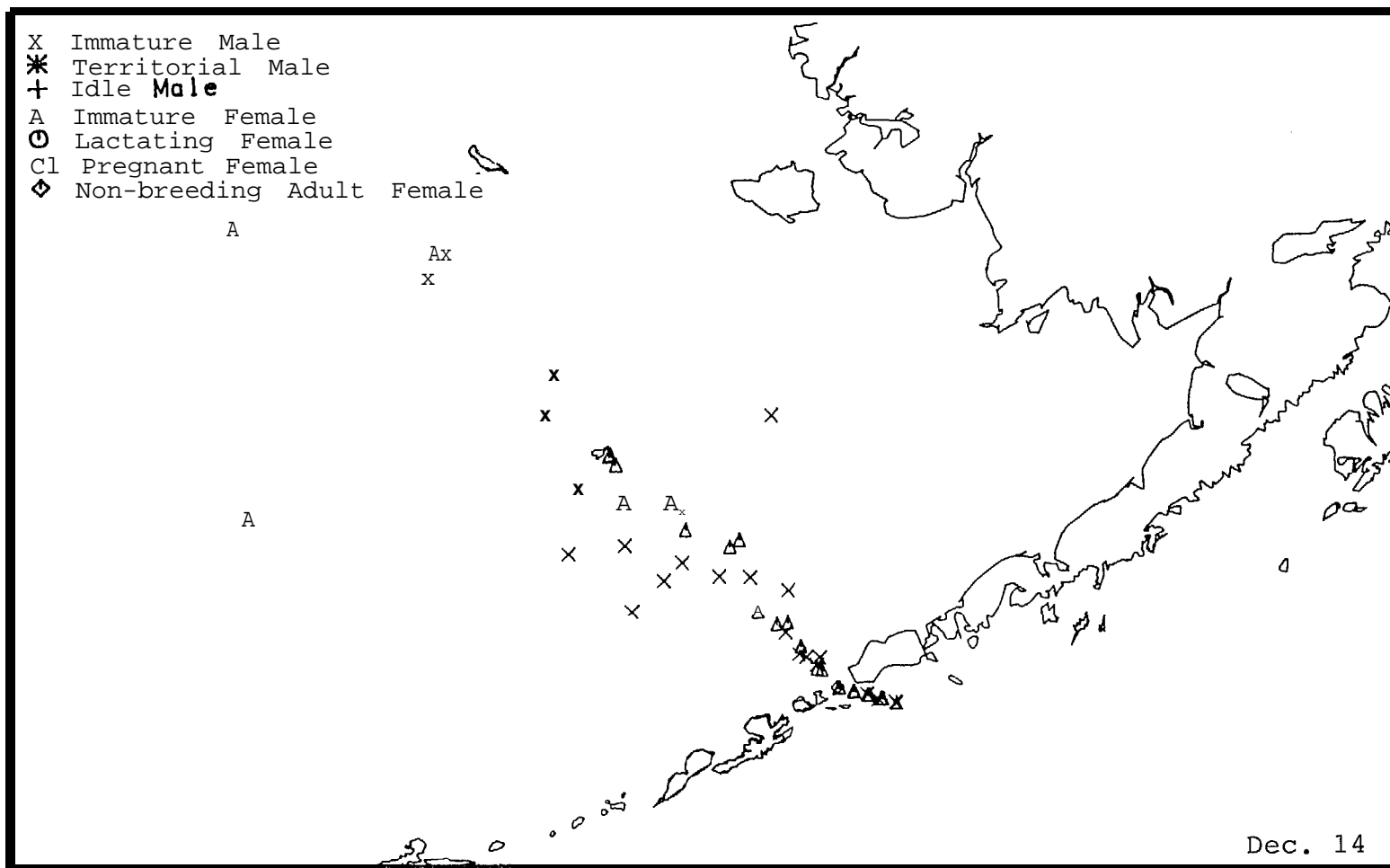


Figure 4-151. Sample distribution of simulated fur seals in the Bering Sea on December 14 (Julian day 348) .

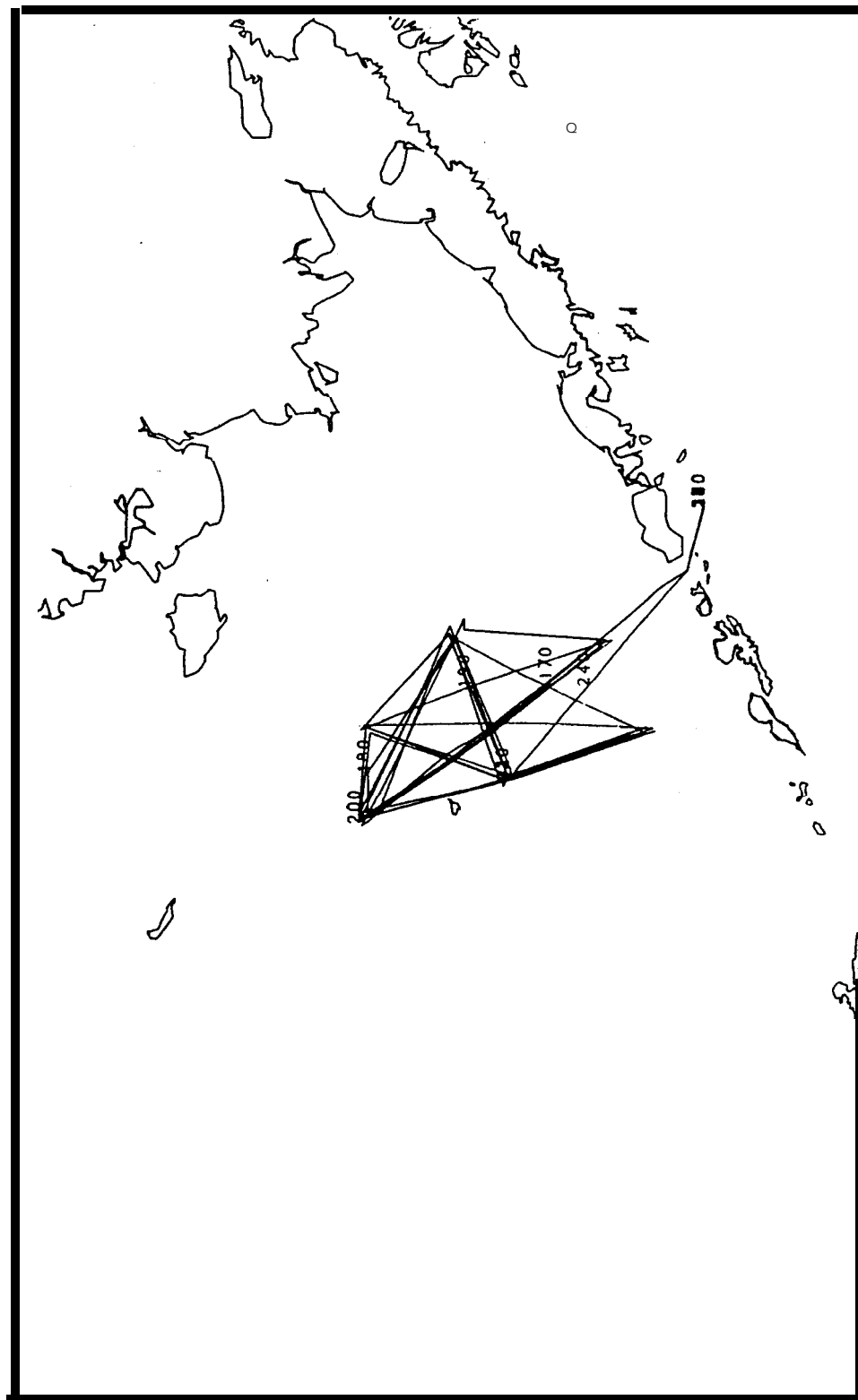


Figure 4-1a. Track of Seal #6 (Immature male). Julian dates are shown at several discrete points along the track.

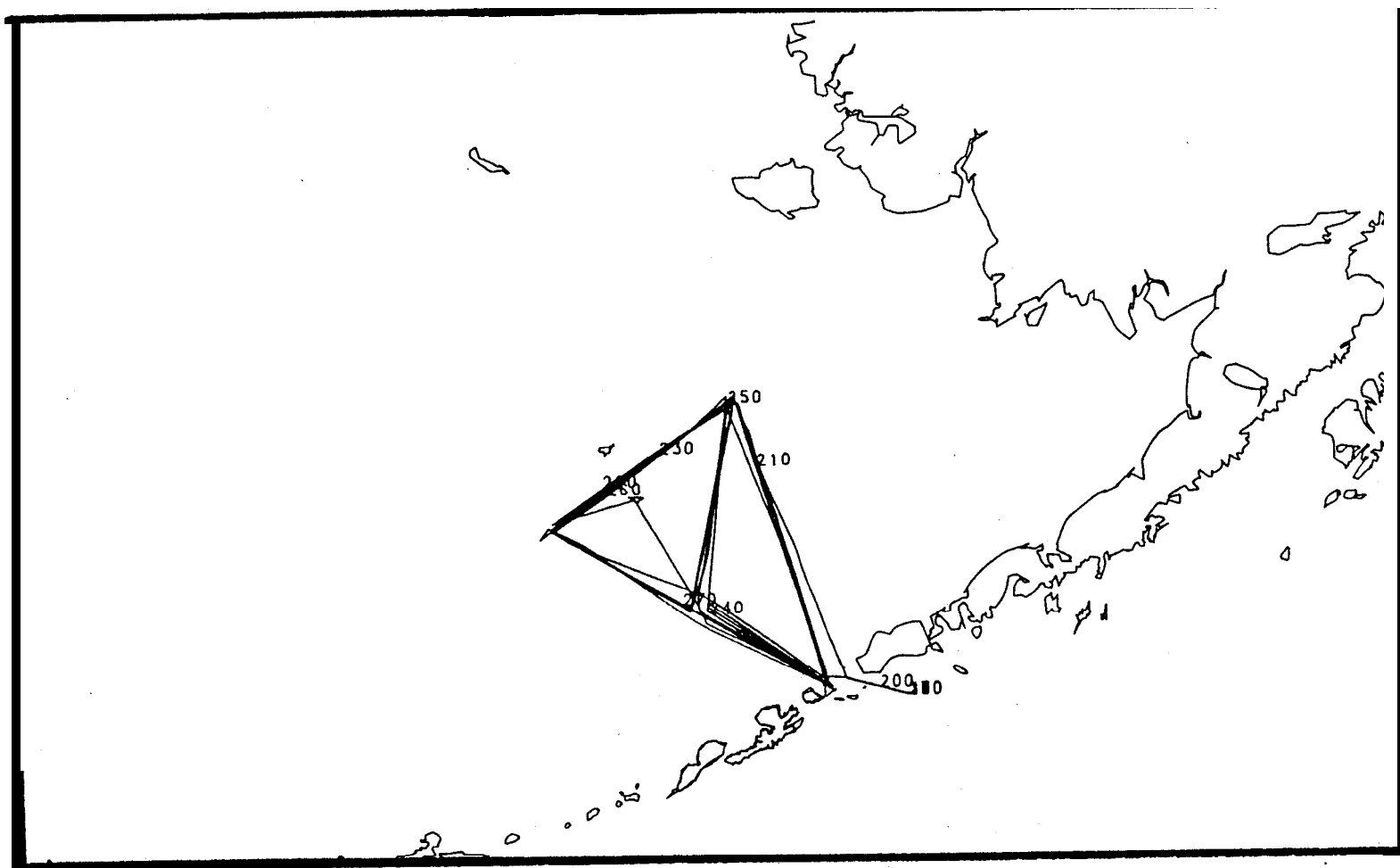


Figure 4-16b. Track of Seal #20 (Immature female). Julian dates are shown at several discrete points along the track.

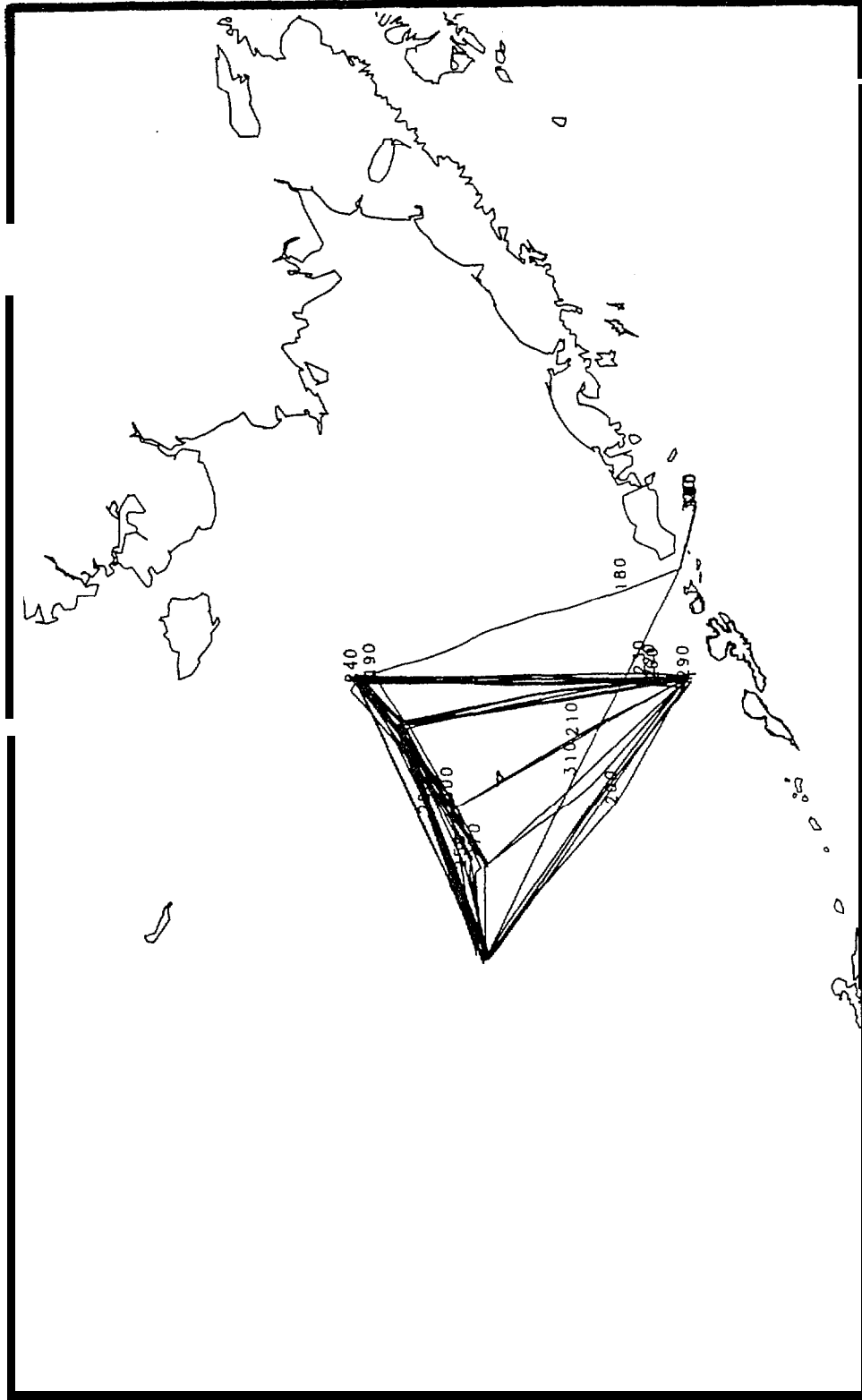


Figure 4-16c. Track of seal #25 (Non-reproductive mature female). Julian dates are shown at several discrete points along the track.

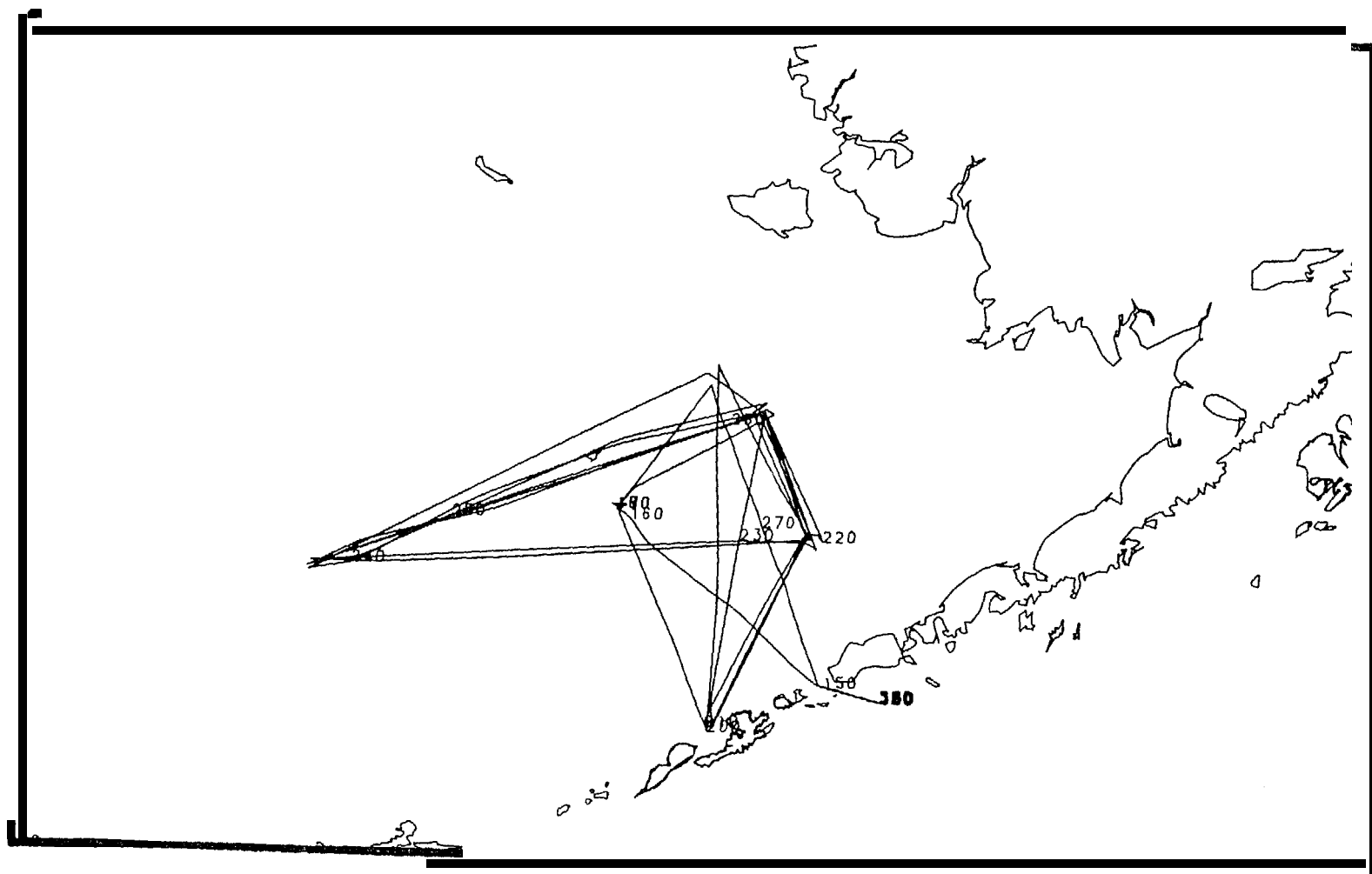


Figure 4-16d. Track of seal #10 (non-territorial mature male) . Julian
shown at several discrete points along the track. dates are

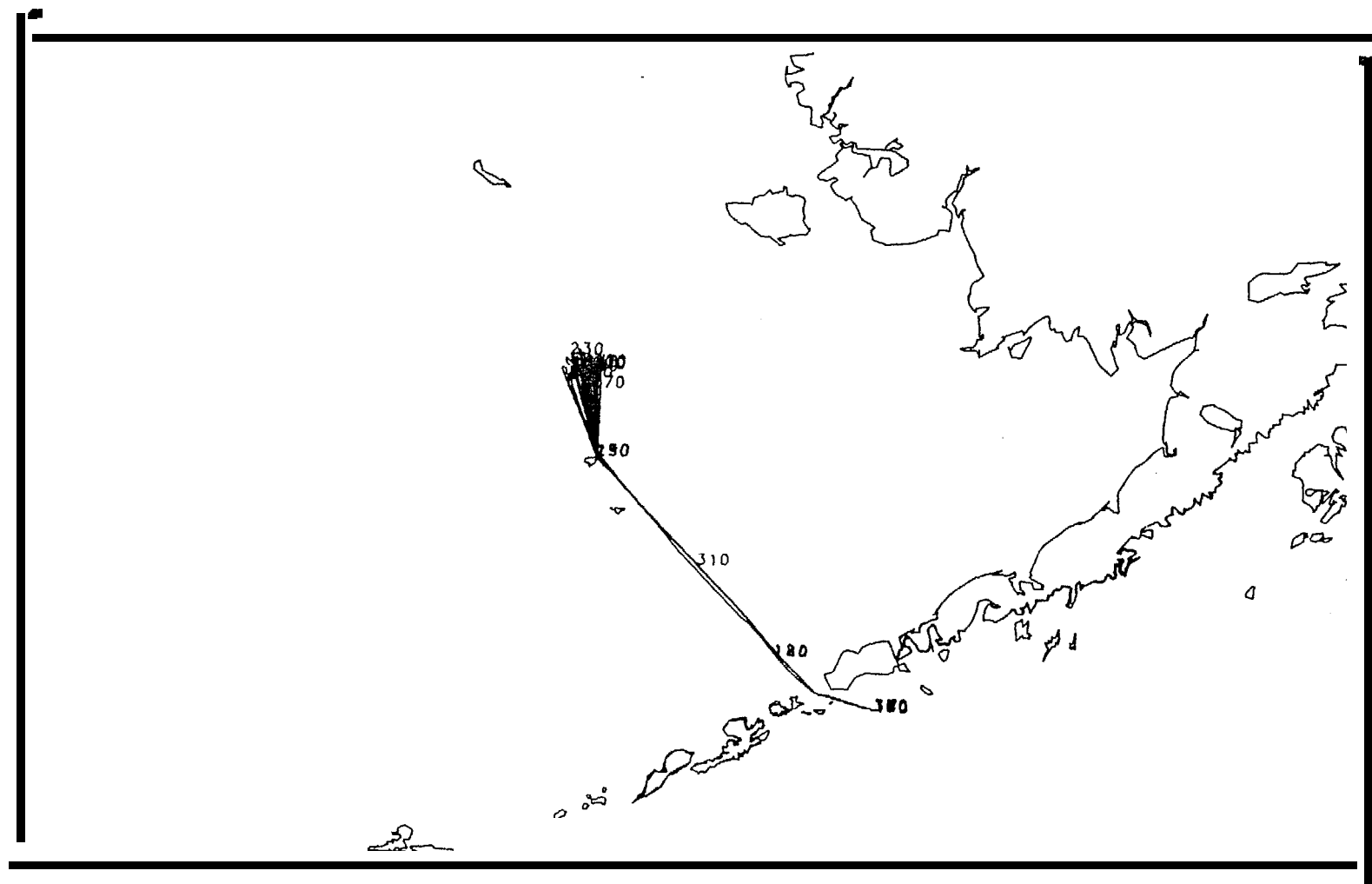


Figure 4-16e. Track of seal #50 (Lactating female).
several discrete points along the track Julian dates are shown at

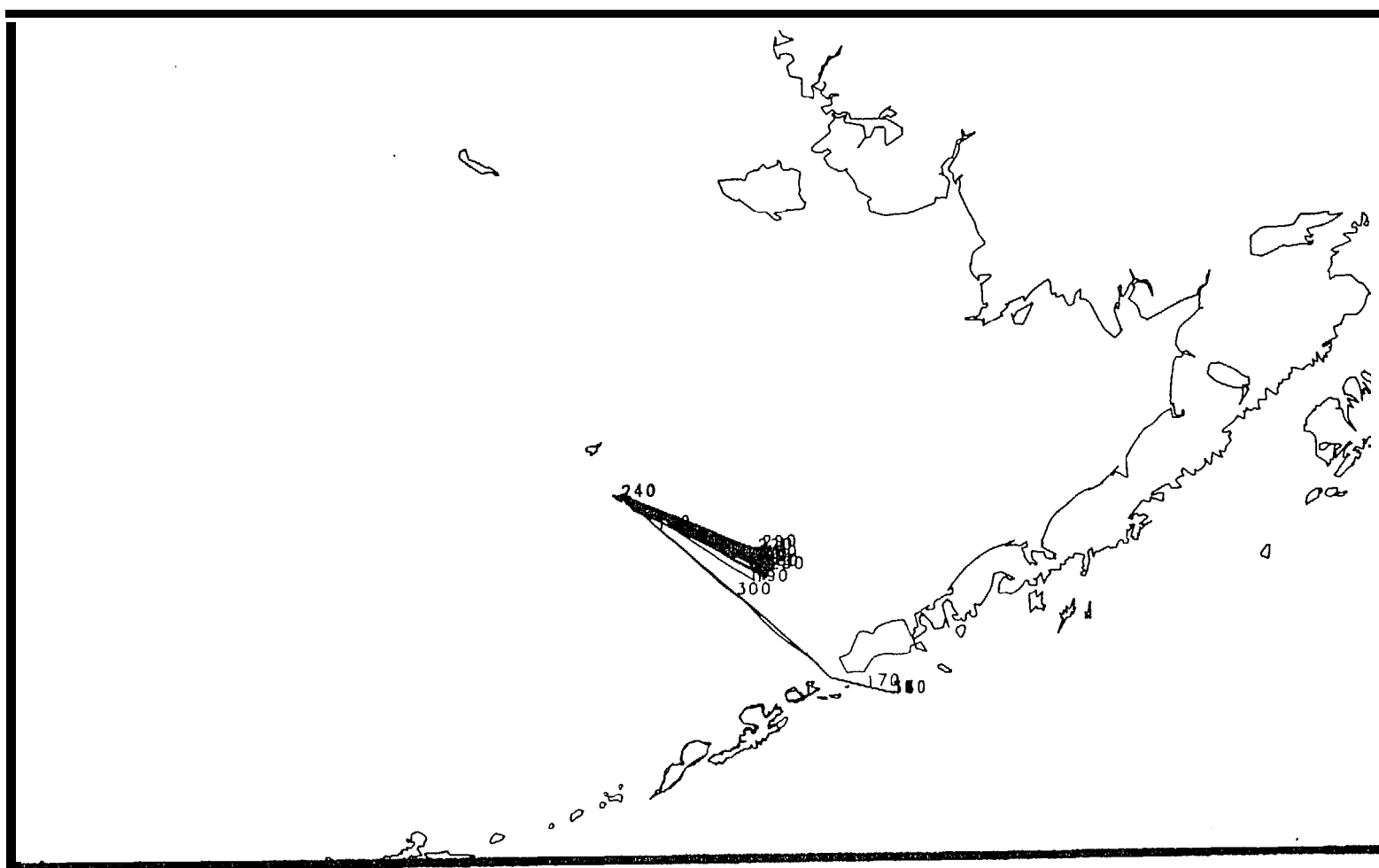


Figure 4-16f. Track of seal #55 (Lactating female) . Julian dates are shown at several discrete points along the track.

Table 4-9. Fit of the migration model to observed feeding distribution as a function of the number of seal points. The equilibrium population has 52 different sexual status and age classes. The # replicates column indicates the number of replicate points of each of the 52 classes which are used to initialize the model. The time step used for the migration model was 6 hours .

# Replicates	# Points	χ^2	χ^2	χ^2
		Lactating Females	Non-breeding Females	Males
1	52	937. **	1715. **	1151. **
5	260	159. **	174. **	403. **
20	1040	57.7	66.9+	79.8 *
40	2080	35.3	55.3	28.8
60	3120	22.3	37.0	19.2
80	4160	18.8	34.4	17.4
100	5200	13.7	31.4	13.7
120	6240	15.7	28.6	11.6
200	10400	10.6	21.1	4.7

** significantly different at P < .01 level

* significantly different at P < .05 level

+ significantly different at P < .25 level

distribution. χ^2 values for 20 or fewer replicate points indicate significant differences from the observed. For 60 or greater replicate points, the probability of obtaining even smaller χ^2 values than those calculated is less than 1%, indicating an excellent fit of the migration model to the observed distribution when this many replicates are used.

For a run of the equilibrium model **population** using 40 replicate points for **each** of the 52 seal types, each point represents 23 to 3063 individual seals on January 1 depending on seal type. For the most numerous types, the male and female pups born the previous summer, points represent the largest number of seals per point, about 3000. Older seals are represented by less than 2000 points, the number decreasing with age. Adult female points represent 23 to 1136 seals each, with a mean of 319 seals per point. For males over 4 years, the mean is 291 seals per point. The overall mean for all seal types is 559 seals per point. For higher numbers of replicate **points**, these values are proportionately lower. Females make up 64% of the equilibrium population by number, and are represented by 73% of the seal points in the migration model.

5. Oil Spill Linkages and Scenario Specifications

5.1 Seal **Model** - Oil **Spill Model** Linkages

The oil spill model used here, and described in further detail in Section 5.2, is based on Reed (1980), **Spaulding** et al (1982), and ASA (1986). Since the presence or absence of seals will have **no** effect on the trajectory of spilled oil, the oil spill **model** is run independently and used to generate spill parameters (**spill** size and location) output at fixed time intervals. The oil spill model output is then input to the fur seal migration model. As a migration simulation proceeds, the position of each seal **point** relative to oil is continuously monitored. To determine the number of seal-oil interactions resulting from a specific spill, the new position of a seal point at the end of each time step is checked relative to the oil distributions. Since seal points and oil spinets are moving simultaneously, intersections may occur which fall between time steps and consequently would not be recorded by **simply** comparing **seal** and oil locations at the end of each time step. The concept of relative velocity is therefore used to determine if an intersection of a **seal's** path with 'the trajectory of an oil spill has occurred during the time step. The velocity and position of each seal point are **re-calculated** relative to the velocity and position of each oil spill (Figure 5-1). If the line describing a seal's relative **movement** intersects the circumference of an oil spill, the **seal** has hit oil. This process is repeated for the life of the spill.

When a seal point encounters an **oil** slick (spinet), it is assumed that all seals represented by that point **are** oiled. Since actual mortality rates of fur seals after oiling are not well **known**, a range of mortality rates is used in tabulating resulting population changes. The assumed oil-induced **mortality** rate determines **what fraction** of the **seals** represented by a single point will die as a result of being oiled. For example, if a 50% oil-induced **mortality** rate is assumed, then **the** first encounter with **oil** results in a **loss of half the** seals represented **by** the point. The time step used for the calculation of mortality is one day. Thus, **re-oiling** may occur on a **daily** basis, but multiple encounters with oil on a single day do not result in further mortalities. Seals **not** dying as the result of oiling on a given day are assumed to recover fully and behave as other seals. However, on subsequent days they may be **re-oiled** and those encounters will result in further mortalities.

5.2 Specifications of Oil Spill Scenarios

Two hypothetical oil spill scenarios have been established in consultation with **MMS** (S. Treaty, personal communication). These are only possible events, with a small probability of occurrence. The total probability of occurrence of one or more **oil spills** exceeding 1000 barrels in the St. George planning area is estimated to be 0.27 (**MMS**, 1985).

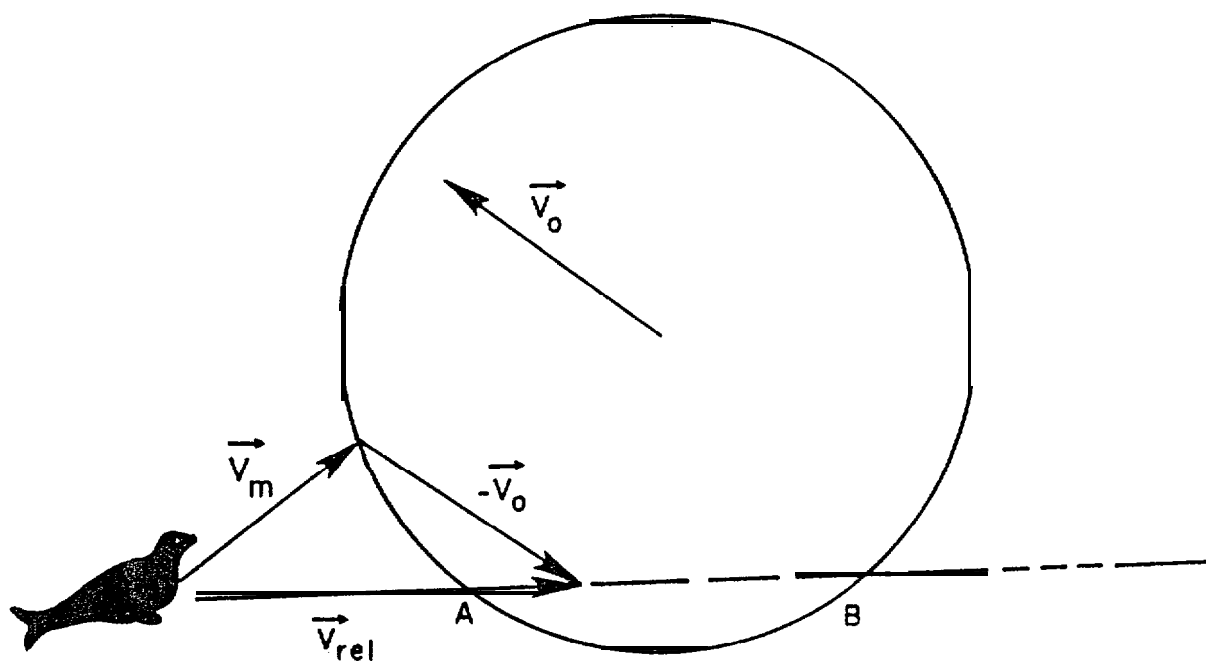


Figure 5-1. Relative velocity, \vec{V}_{rel} , of a seal with respect to an oil spill. \vec{V}_o is the velocity of the oil spill, and \vec{V}_m is the velocity of the seal relative to a fixed reference frame.

Spills which occur between December 1 and April 30 will not directly affect fur seals since they are not in the Bering Sea at **that** time. **If** spill occurrence probabilities are assumed **uniformly** distributed over the year, the probability of a spill occurring while fur seals are in the area is reduced to about 0.16. Likewise, **.if** the probability of a spill exceeding 1000 barrels striking the **Pribilofs** within 10 days of release is about 0.03 (**Samuels**, 1984), the probability of such **an** occurrence while fur seals are in the area is about 0.02. The **hypothetical** spill scenarios simulated here, each of 10,000 barrels, have even smaller probabilities of occurrence.

One simulated spill affects St. Paul Island in July, when maximum numbers of seals are present at **the** rookeries. The second is near Unimak Pass during the northbound migration in the spring. In each case, a release of 10,000 barrels of **Prudhoe** Bay crude **oil** is simulated for 10 days. One fifth of the total **mass** is released at time zero, **and** every three hours thereafter for 12 hours. Each of these "sub-lots" of oil forms an individual oil patch, or spinet (Figures 5-2 and 5-3).

The evaporation of hydrocarbons from each spinet is computed according to the model reported by Payne et al (1984), which uses the rate calculation of MacKay et al (1980). For an oil characterized by a series of boiling point fractions, the evaporation rate of the i^{th} fraction is given by

$$dM_i/dt = K_i P_i A f_i / RT$$

where

P_i = vapor pressure of fraction i (atm)
 A = slick area (m^2)
 f_i = molar fraction of i remaining in slick
 R = gas constant (8.206×10^{-5} atm- m^3 /g-mole- $^{\circ}K$)
 T = temperature ($^{\circ}K$)

The mass transfer coefficient K_i is computed by

$$K_i = 0.014 U^{0.78} D^{-0.11} \sqrt{(MW_i + 29)/MW_i}$$

in which

u = wind speed (m/hr)
 D = slick diameter (m)
 MW_i = molecular weight of fraction i

JULY OIL SPILL IMPACTING ST. PAUL ISLAND

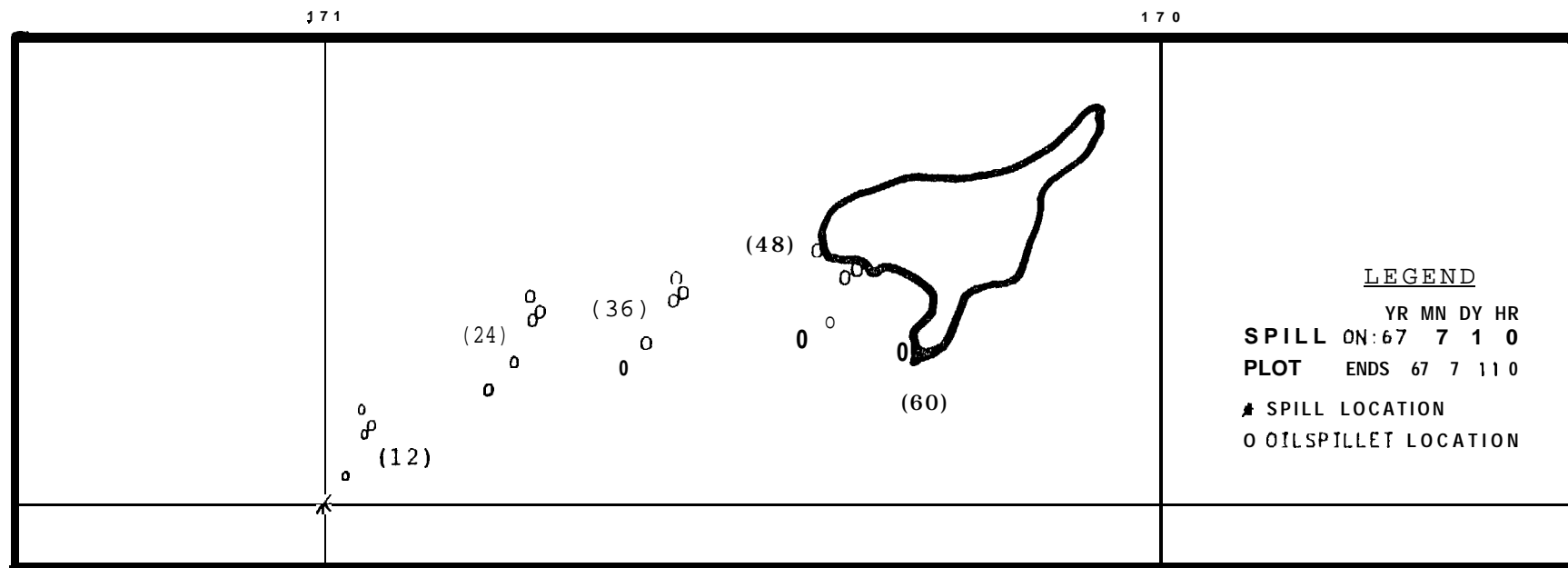


Figure 5-2. Sequential positions of surface oil spinets following a hypothetical 10,000 barrel release from 57° N, 171° W. The weather scenario is from July of 1967. Numbers in parentheses are hours since release of the first spinet.

LATE JUNE OIL SPILL NEAR UNIMAK PASS

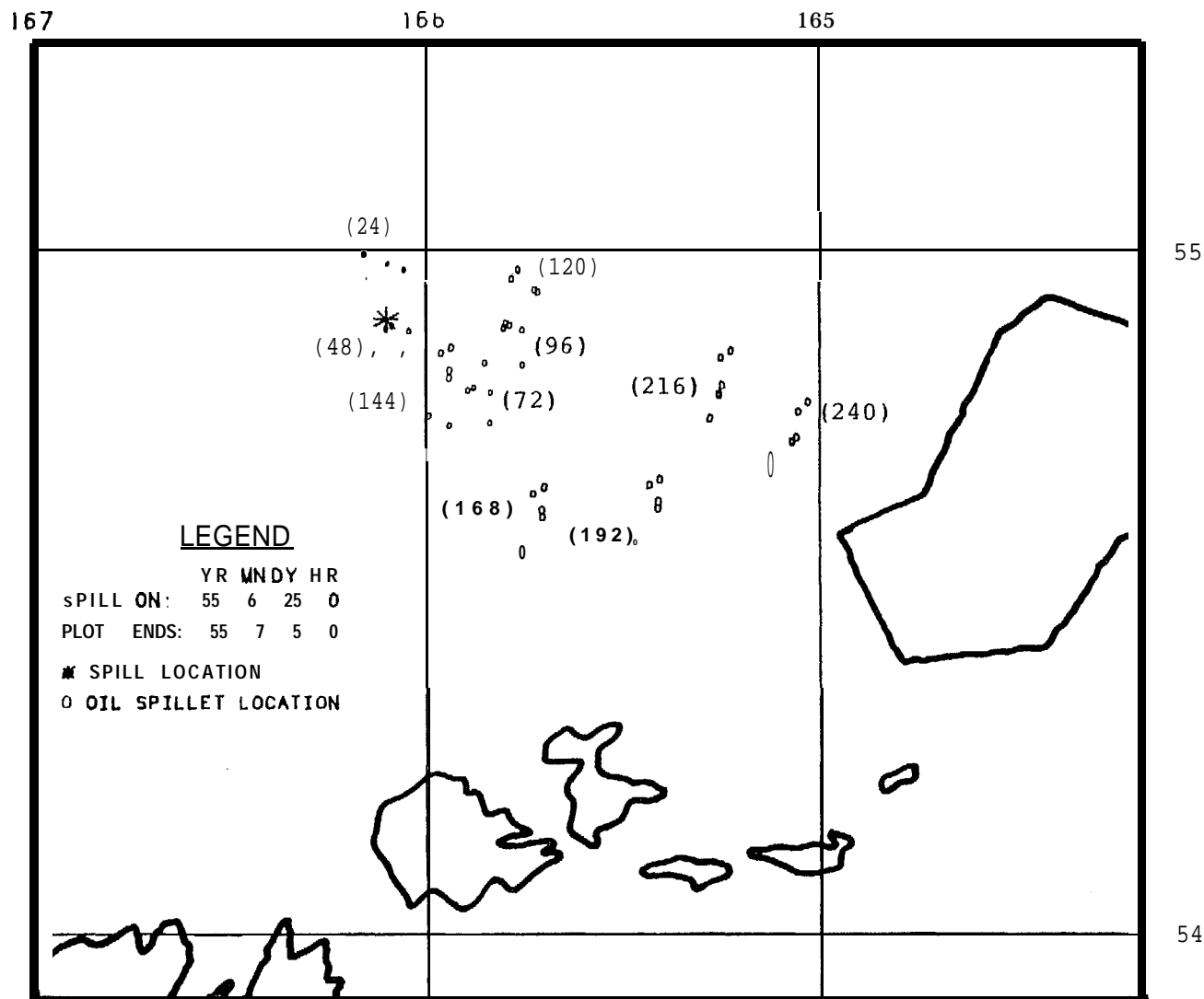


Figure 5-3. Sequential positions of surface oil spinets following a hypothetical 10,000 barrel release from 54.9° N, 166.1° W. The weather scenario is from June-July, 1955. Numbers in parentheses are hours since release of the first spillet. The mean position of the spill goes through two spirals as a result of two storm events which passed through the area.

The spreading algorithm is the "thick slick" formulation discussed by MacKay et al (1980), and is derived directly from the gravity-viscous equation developed by Fay (1971). According to this formulation, the rate of change of slick area A is given by

$$dA/dt = K_2 z^{1.33} A^{0.33}$$

where

A = slick area (m²)
 z = slick thickness (m)
 K₂ = a constant ≈ 150

The entrainment/dispersion of oil into the water column from the surface slick is based on Spaulding et al (1982) in which the dispersion rate F is computed as

$$F = 0.1(U^2/U_o^2) e^{-rt}$$

where

U. = reference wind speed (8.5 m/sec)
 r = constant (0.5 per day)
 t = time (days)

The surface area and mass balance of a 2000 barrel spinet are given in Table 5-1 as **functions** of time since release. The surface area given represents the total area covered by oil; the model assumes that coverage within a spinet is continuous, not patchy. The model checks at every timestep to be certain that the remaining mass of oil in each spinet is sufficient to cover the projected area at or above the minimum thickness. Spreading results are on the low side of the correlation reported by Ford (1985), **but** the text of that report leaves it unclear whether the **areal** coverage estimates include open areas between smaller patches of oil. The modeled **areal** coverage refers only to oil-covered water.

Horizontal transport of the oil is computed by hydrodynamic and wind/weather models used by Applied Science Associates, Inc. for other applications (ASA, 1986; Isaji and Spaulding, 1984).

The oil spill model applied here **does** not resolve nearshore processes, but simply brings oil slicks **uptothe** coastline and stops. It is expected that **oilwhichdirectly affects a rookery may result in** oiling of a large **number** of seals, **which** typically enter the water at least once

Table 5-1. Simulated surface area and mass balance for a 2000 barrel spill of Prudhoe Bay crude oil at 60° F and a wind speed of 5 m/sec.

Time (Days)	Surface Area (km ²)	Fractional Mass Balance "		
		Water Surface	Atmosphere	Water Column
1	0.34	0.806	0.118	0.077
2	0.44	0.766	0.134	0.100
3	0.53	0.748	0.144	0.109
4	0.59	0.737	0.151	0.112
5	0.65	0.731	0.157	0.113
6	0.71	0.725	0.161	0.113
7	0.76	0.721	0.166	0.113
8	0.81	0.717	0.169	0.113
9	0.86	0.714	0.173	0.113
10	0.91	0.711	0.176	0.114

per day (Gentry, 1981). Therefore, the anticipated behavior of oil in the nearshore zone must be explicitly described in quantitative terms based on observations of actual spill events.

The coast of the Pribilof Islands is typically rocky, so that observations of oil behavior during the Amoco Cadiz and Urquiola spills can provide a basis for comparison (Gundlach et al, 1985). During those spills, it was observed that wave reflection from rocky shores tended to hold surface oil 10-30 meters offshore depending on the wave height. At the same time, the onshore winds that brought the oil to the coast continued to drive the oil into more sheltered areas, and those areas of the coast which were composed of cobble and gravel and therefore poorly reflect wave energy. To some extent, then, the oil will be advected alongshore and continue weathering as in open water. As the slick proceeds alongshore, some of the oil will be captured in sheltered embayments.

Based on the above discussion, and the specific trajectories and points of initial coastal contact of each of 5 spinets released during each spill, we postulated the following nearshore behavior scenarios for each spinet.

(1) July Oil Spill Impacting St. Paul Island

Spinets 1-3. These spinets came ashore west of Zapadni, about 48 hours after release (Figure 5-2). It is probable that oil moving alongshore would be entrapped in the embayment to the west of the point (Figure 5-4). Although the coast near Suthetunga might be oiled, no fur seal rookeries are presently located in this area. Only seals swimming through these areas would possibly be affected.

Spinets 4 and 5. These two spinets, representing about 30% of the total oil spilled after accounting for evaporation and entrainment, came ashore on the southern tip of St. Paul Island about 60 hours after release. It is probable that this oil would be herded by the

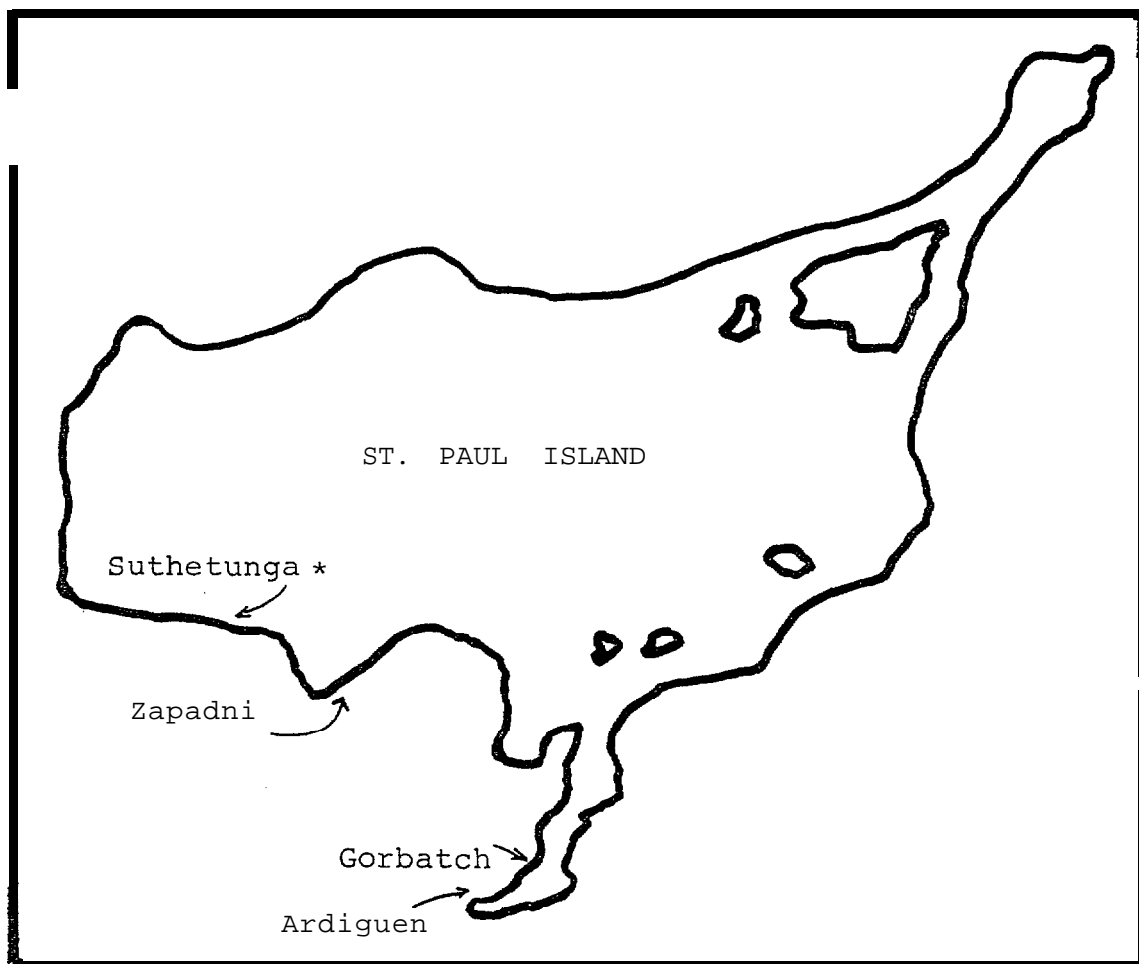


Figure 5-4. Map of St. Paul Island showing active and extinct (*) fur seal rookeries on the southern coast.

wind and waves along the coast where the **Gorbatch** and **Ardiguen** rookeries are located, The oil would continue to weather in the nearshore surf zone, and be reduced to a relatively heavy asphalt-like substance after about 10 days (**Gundlach** et al 1985). During the intervening time period, it is expected that all seals entering the water from these rookeries **would** possibly **be** oiled to some extent. Thus, two extreme cases were assumed for this spill in the fur-seal-oil interaction simulations. In one case, all seals located on one of these 2 rookeries during the time oil was present on the shore were oiled. Thus, it was assumed that all **seals** on the rookery enter the nearshore zone at least once during the day. In the second case, it is assumed that only those seals leaving or arriving on the rookeries were oiled as they passed through the spinet. Thus, pups and other animals which remain on the rookeries throughout the spill were assumed not to enter the nearshore zone while-oil was present.

(2) June Oil Spill Near **Unimak** Pass

The oil spill simulated near **Unimak Pass** did not come ashore and is unlikely to do so in further simulation, so no near-shore assumptions were required for this analysis.

6. Model System Sensitivity Studies

6.1 Fur Seal Population Dynamics **Model**

To test the stability of the population dynamics **model**, the equilibrium population of 1.16 million seals was reduced to 98%, 95%, 90%, 80%, 60% and 40% of the equilibrium **population** proportionately across all age and sex classes (Figure 6-1a through f). These results show population dynamics behavior associated with losses of seals, **due** for example to **harvesting** or an oil spill. Because the age class structure was unaltered in these simple tests, the population returned smoothly to equilibrium. When the population was reduced by up to 10%, the return to equilibrium was complete within 25 years (Figure 6-1a, b, and c). Recovery from more extreme reductions took longer (Figure 6-1 **d,e,f**).

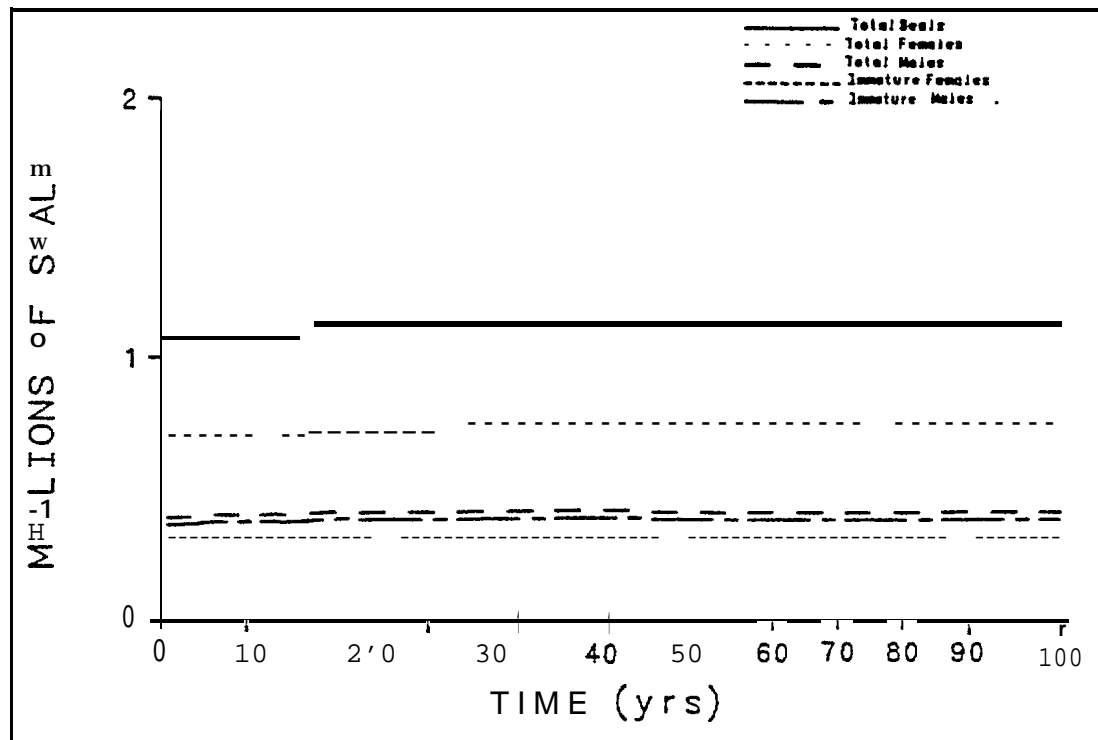
When the 1950s population simulation of Figure 4-8b was perturbed, recovery was more rapid (about 10 to 15 years to recovery, Figure 6-2 a and b). This was due to the fact that the density-dependence of female juvenile survival **was** stronger in the 1950s population simulation than in the 1.16 million standard equilibrium population. The lack of information on female juvenile survival makes the resolution of this discrepancy impossible. The recovery rates from the oil spill scenarios reported **here** are, therefore, conservative estimates.

Figure 6-3 shows the recovery of the current (1986) population to **the** 1950s population level, assuming the differential female juvenile survival rate is accurate, that all entanglement mortality is removed and male harvest ceases. The simulated population overshot the steady-state level slightly after 25 years, and then quickly returned to the steady-state oscillation. If male harvest is assumed to continue at 1970's levels (as in Table 4-1), the results are not significantly different.

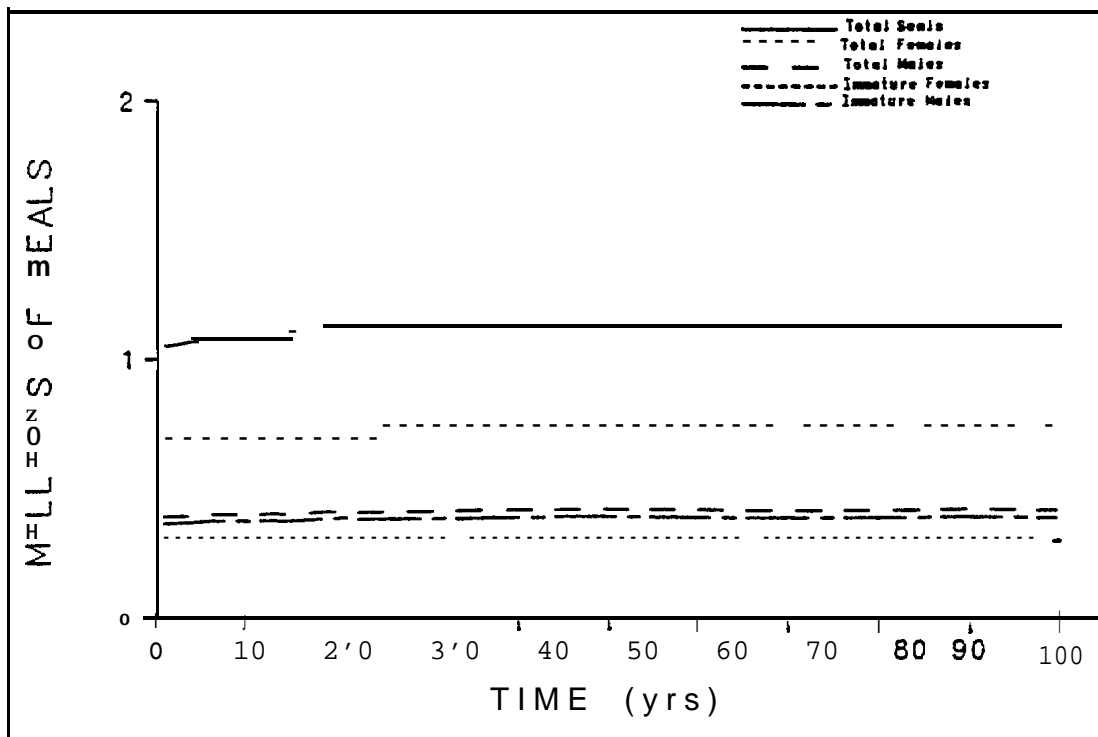
6.2 Migration **Model** Feeding Distribution

The effect of the migration **model** time step and the number of **seal** points on the fit of the model distribution to the observed seal distributions was tested using χ^2 as defined in Section 4.2 (Table 6-1). The time step must be less than or equal to one day in order to resolve the daily movement patterns of the fur seals. The simulated feeding distribution was not significantly different from the observed for a timestep of 3 to 24 **hours** and at least 40 replicate seal points. Use of 60 replicate points, however, greatly improved the distribution of males and to a lesser degree, that of females. The migration model was not sensitive to time steps between 3 and 24 hours in terms of fit to the observed distribution.

In the migration model, a random number **generator** provides data which selects which seal points go to each of the various feeding areas, the



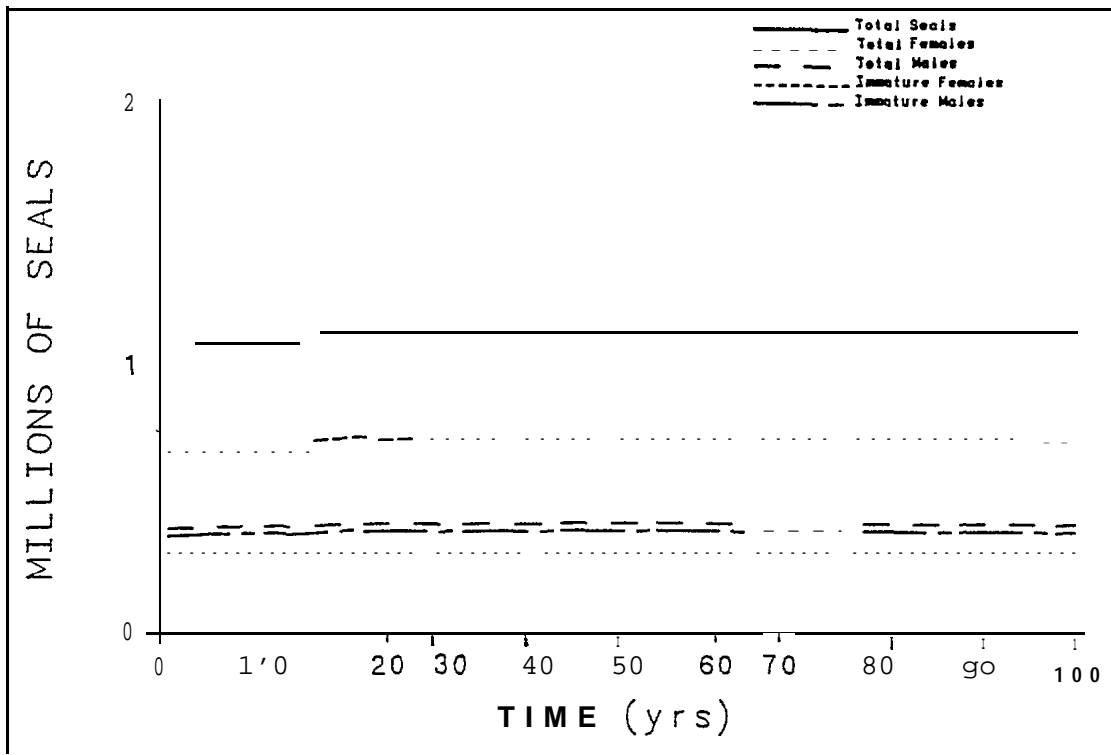
(a)



(b)

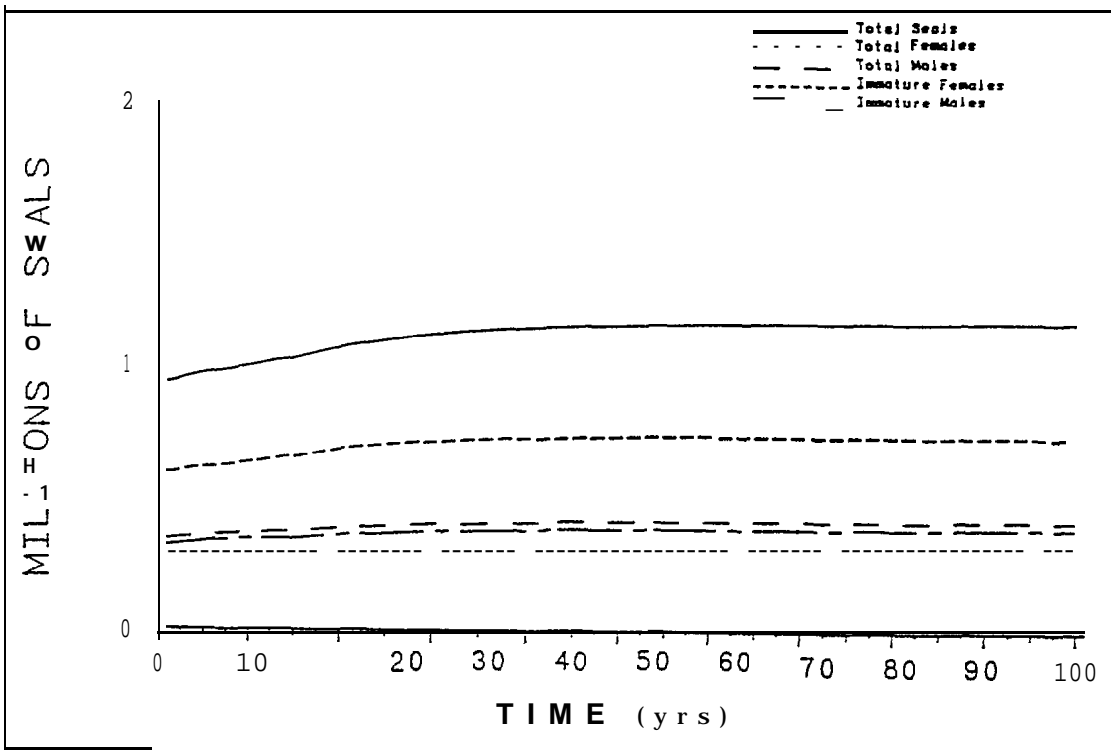
Figure 6-1. Recovery following perturbation of the equilibrium population. Seal numbers are plotted once per year (on January 1) . Population reduced to (a) 98%, (b) 95% of initial size.

no_pert9



(c)

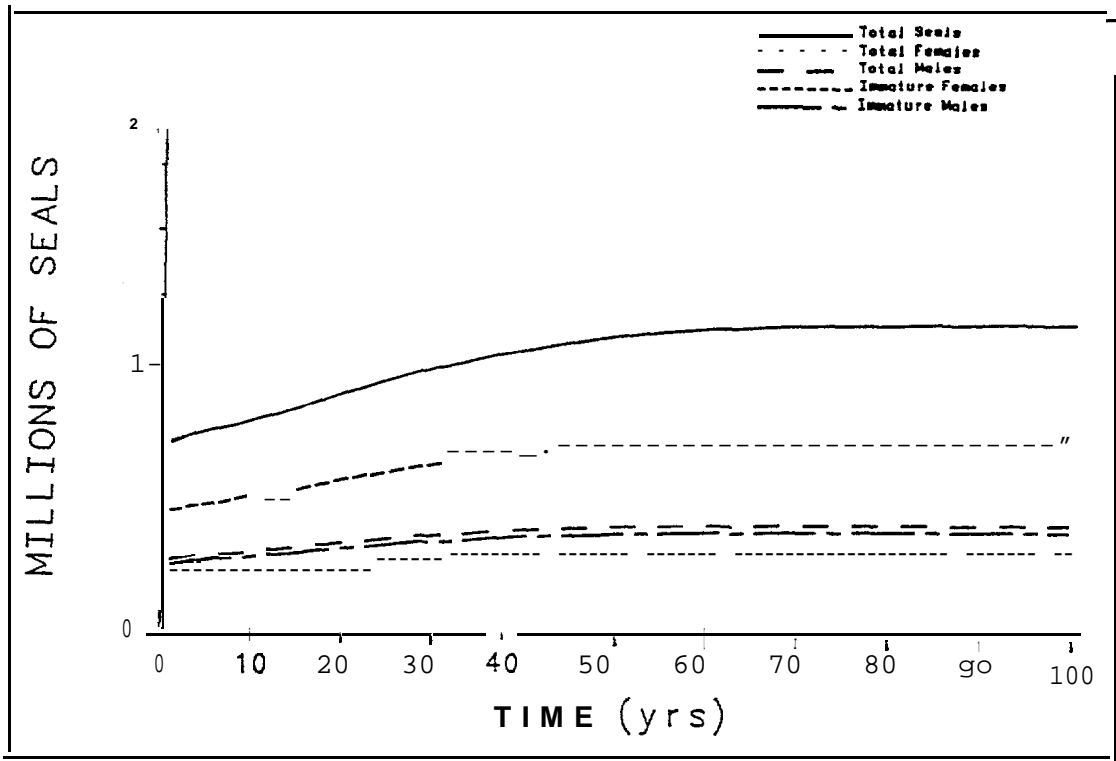
no_pert8



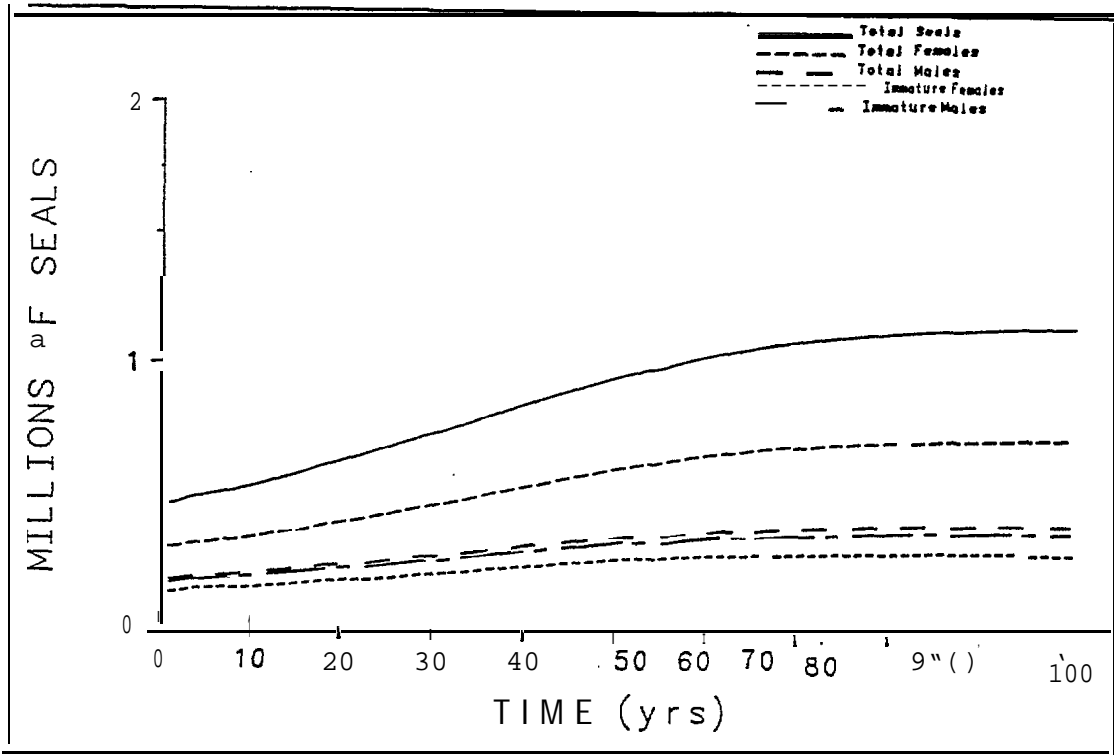
(d)

Figure 6-1. Recovery following perturbation of the equilibrium population. Seal numbers are plotted once per year (on January 1). Population reduced to (c) 90%, (d) 80% of initial size.

no_pert6



(e)



(f)

Figure 6-1. Recovery following perturbation of the equilibrium population. Seal numbers are plotted once per year (on January 1.) Population reduced to (e) 60%, (f) 40% of initial size.

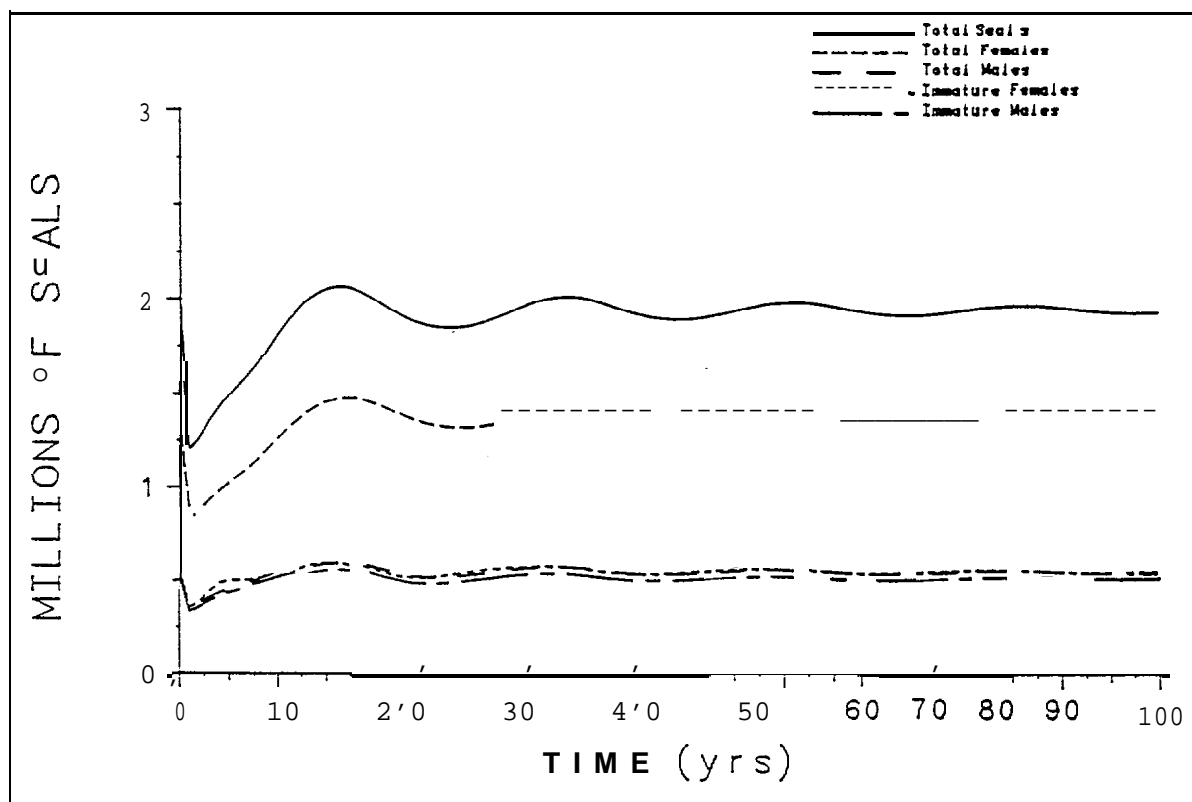
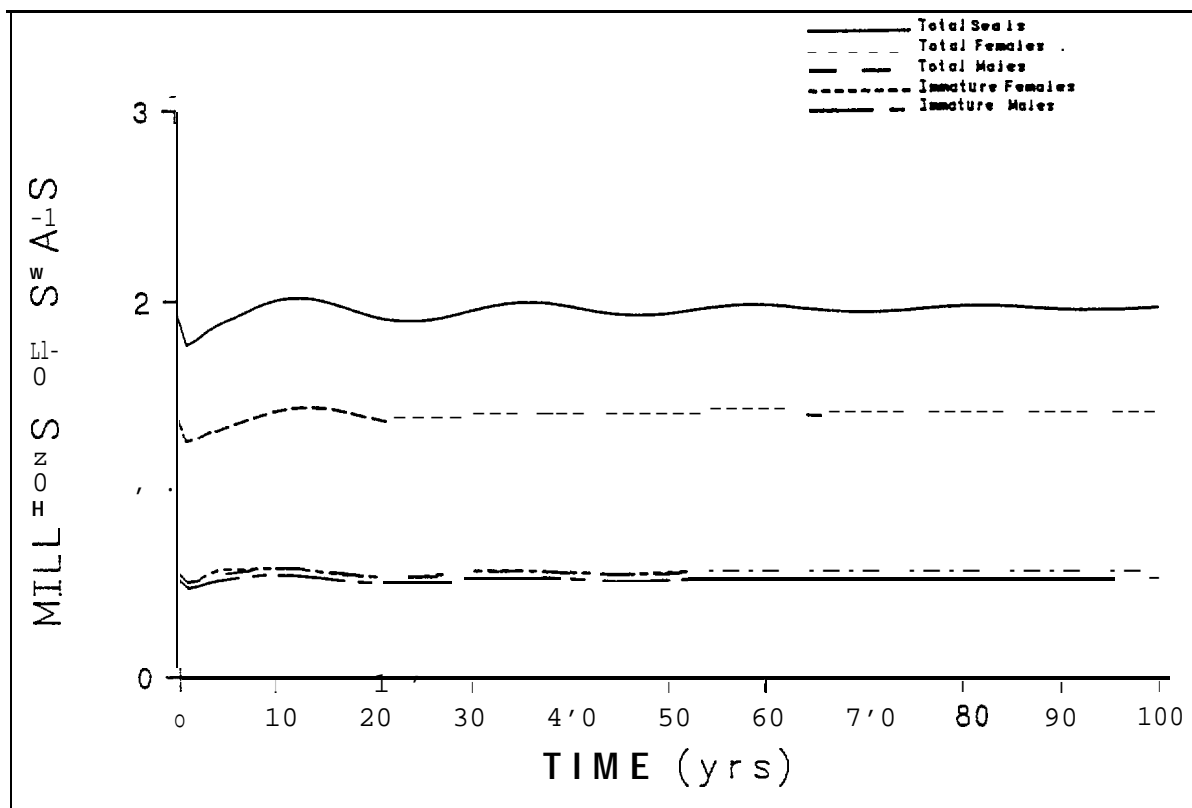


Figure 6-2. Perturbation of the simulated 1950s population. Population reduced to (a) 90%, (b) 60% of the equilibrium population size of Figure 4-8b.

no_F1986H

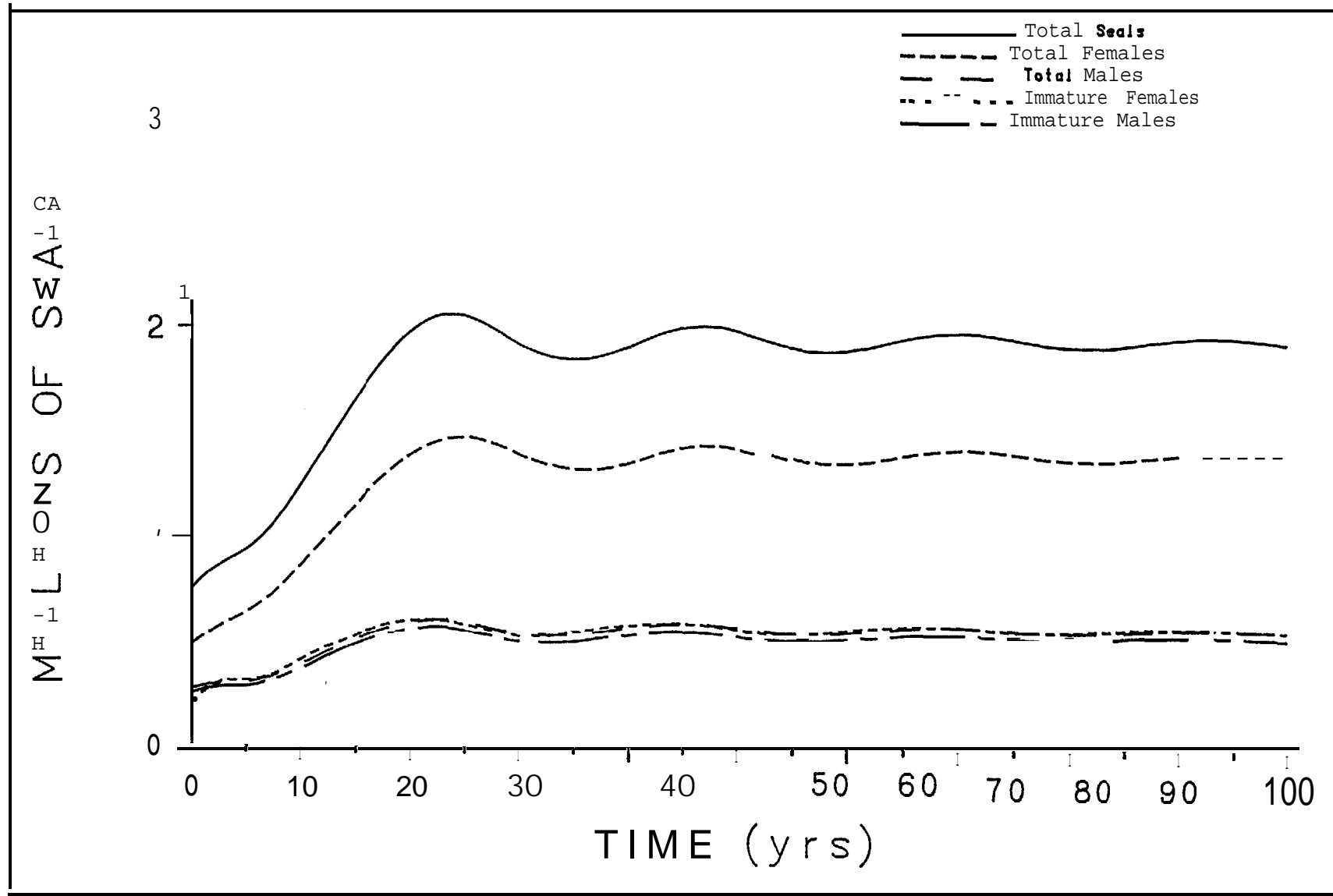


Figure 6-3. Simulation of the recovery of the 1986 population following removal of entanglement mortality and male harvest.

Table 6-1. Fit of the migration model to the observed feeding distribution as a function of time step (At). There was no significant effect of time step or number of points within the ranges given. The modeled distribution was not significantly different from the observed feeding distribution for any sexual class,

<u># Replicates</u>	<u># Points</u>	<u>At (hrs.)</u>	<u>x ' Lactating Females</u>	<u>x ' Non-Breeding Females</u>	<u>x ' Males</u>
40	2080	3	34.3	66.7	37.4
		6	35.3	55.3	28.8
		12	39.3	48.4	37.7
		24	37.9	54.3	28.2
60	3120	3	30.3	44.8	15.7
		6	22.3	37.0	19.2
		12	28.7	43.9	18.9
		24	30.3	44.8	15.7
80	4160	3	22.4	30.0	17.6
		6	18.8	34.4	17.4
		12	21.6	34.9	15.9
		24	22.6	41.5	14.2
100	5200	3	19.3	36.7	11.7
		6	13.7	31.4	13.7
		12	19.9	25.3	12.0
		24	19.7	30.5	13.5

Table 6-2. Variation in the fit of the migration model to the observed feeding distribution resulting from different initial seeds to the random number generator. For all runs of the model, 60 replicate points and a time step of 3 hours were used.

<u>Seed #</u>	<u>x ' Lactating Females</u>	<u>x ' Non-Breeding Females</u>	<u>x ' Males</u>
1	30.3	44.8	15.7
2	27.0	60.8	23.6
3	19.0'	37.8	22.3
4	26.7	31.5	18.7
5	27.6	53.1	22.4
6	21.4	49.1	21.8
7	27.7	46.6	17.9
8	24.9	37.7	17.7
Mean	25.6	45.2	18.8
Standard Deviation	3.7	9.4	5.2

timing of movements within the Bering Sea for non-breeding **seals**, and the variability in swimming velocities. By seeding the random number generator with different values, a different random number sequence is obtained. As shown in Table 6-2, variation **of** the random **number** seed does not affect the fit of the **model** to the **observed** seal distributions. The standard deviation provides a measure of variability in the migration model.

6.3 Fur Seal - Oil Spill Interactions

The migration model was run with the **Unimak** Pass oil spill described in Section 5.2, using a range of time steps and various numbers of seal points. It is apparent from Table 6-3 that both **the** time step **and** the number of seal points have a considerable influence on the resulting number of seals oiled. Use of a longer time step reduces the number of seals oiled in the simulation. This is because the larger time steps lose the more detailed resolution of both the seal and oil slick movements, introducing what are known as **aliasing errors** in time series analysis. Use of too few seal points fails to reproduce accurately seal densities at spatial scales commensurate with typical spinet sizes (i.e., 0.5 to 1 **km²**). The limit to the temporal resolution of the oil spill model is 3 hours due to the resolution of weather data, so a further decrease in **the** time step **would** not provide more accuracy. The three hour time step has been used in all further fur seal-oil spill interaction runs.

A series of simulations using 8 different random number seeds was performed to determine the relationship between the **number** of seal points used to represent the population, and the number of seals encountering oil during a given simulation. The results of these simulations (Table 6-4) showed that (a) increasing the number of replicate seal points beyond 60 resulted in negligible changes in the mean values of the number of **seals** oiled, and (b) multiple runs using different random number seeds are needed **to** obtain an accurate estimate of the number of seals oiled by a spill scenario. The percent variability in the number of males oiled was higher than that of females for two reasons: (1) there were fewer male seal types than female seal types and so were fewer male **seal** points for a given number of replicates; and (2) **the** simulated **Unimak** spill **occured** at the peak of female migration through **Unimak** Pass and after **most** males had passed by, so there were fewer male seal points to potentially oil. Since male seal **numbers** are only weakly related to future population size and dynamics in the model, the larger error associated with males was inconsequential. Fur seal - oil spill interaction simulations have therefore been carried out with 60 replicate points for each of the 52 seal types (age, sex, sexual status), or 3120 points **total**. Table 6-5 shows the number of seals per point by seal type in these interaction simulations. The overall average was 373 seals per point for **the** equilibrium population and 235 seals per point for the 1986 population (both January 1).

The **oil** spill simulations reported here are for 10,000 barrels of **oil**

Table 6-3. The effect of migration model time step and number of seal points on number of seals oiled by the simulated oil spill near Unimak Pass. An equilibrium population of 1.16 million seals was **assumed**. Values given are for the mean (and standard deviation in parentheses) of 8 runs using different random number seeds.

	# replicates	40	60	100	140
	# points	2080	3120	5200	7280
<hr/>					
Time Step					
(Hrs.) :					
Mean Number of Females Oiled (Standard deviation)	3	23242	21519	21121	20933
		(4213)	(3028)	(2006)	(1402)
	6	18607	19900	20978	19222
		(3003)	(2989)	(2246)	(1852)
	12	14768	14038	17142	16052
		(2299)	(1664)	(1594)	(1943)
	24	12901	12357	12616	12762
		(2880)	(1394)	(1871)	(1631)
Mean Number of Males Oiled (Standard	3	2354	2059	1879	1622
		(1253)	(898)	(591)	(632)
	6	2179	1630	1874	1461
		(1307)	(636)	(863)	(703)
	12	1895	1790	1395	1341
		(1000)	(774)	(660)	(702)
	24	1641	1623	1109	1255
		(1792)	(1134)	(397)	(386)

ble 6-4. Variation in the number of seals oiled by the simulated Unimak Pass spill as a result of the number of seal points used in the migration model and of variation of the random number generator seed. The timestep was 3 hours and the equilibrium population was used. *M* = mean, *S* = standard deviation, *F* = result of one way analysis of variance for *df* = 5, 42 indicating no significant difference in means over the range of 60 to 200 replicate points.

	Number of <u>Seed</u>	Number of Replicate Seal Points							
		<u>20</u>	<u>40</u>	<u>60</u>	<u>80</u>	<u>100</u>	<u>120</u>	<u>140</u>	<u>200</u>
Number of Females Oiled (<i>F</i> = 0.062)	1	19311	17905	20533	24514	23223	26051	21534	19855
	2	21012	26249	20958	23684	21870	20926	18993	24218
	3	20710	22339	25593	23187	21152	22963	21664	21397
	4	21727	21930	24278	21878	18040	20605	18925	20451
	5	21511	26814	17034	16012	21452	21715	20569	22022
	6	27138	23839	18077	20541	24185	19463	20837	20504
	7	31845	17474	24108	21371	18513	22629	22150	19348
	8	25365	29388	21572	20570	20842	23741	22788	22684
	<i>M</i>	23577	23242	21519	21470	21121	22262	20933	21310
	<i>S</i>	4225	4213	3028	2639	2006	2064	1402	1613
Number of Males Oiled (<i>F</i> = 0.953)	1	2822	1386	2401	629	2912	1593	677	1918
	2	4630	390	2488	1570	2348	1611	1890	1427
	3	116	4337	1866	992	2232	1724	2500	2018
	4	778	2487	3446	2272	1066	1573	2044	2014
	5	2174	3475	1472	1498	1686	2216	1244	2161
	6	0	2970	1285	2736	1371	1496	1003	1880
	7	0	1594	2818	677	1618	822	1431	1463
	8	2194	694	1252	1799	775	2186	1952	
	<i>M</i>	2354	2059	1453	1879	1476	1622	1854	
	<i>S</i>	1253	898	743	591	474	632	266	

Table 6-5. Number of seals represented by each of 60 replicate seal points as a function of seal **type** (age, sexual status) for the equilibrium population on January 1 (Table 4-2). The numbers of seals per point for the 1986 population on January 1 (Table 4-5) are 63% of these values.

<u>Age</u>	<u>Pregnant Females</u>	<u>Non-pregnant Females</u>	<u>Males</u>
0	0	2038	2042
1	0	1328	1318
2	0	970	937
3	0	846	731
4	32	757	557
5	275	468	417
6	490	210	305
7	530	133	220
8	538	95	157
9	519	78	112
10	485	66	76
11	446	61	49
12	400	55	30
13	345	52	17
14	290	55	0
15	232	54	0
16	168	50	0
17	112	46	0
18	65	38	0
19	35	28	0
20	15	17	0
Average	293	3 5 5	498

spilled in an area and at a time when there is a **high** density of seals. Thus, the grouping of seals into points of a few **hundred** seal-s each does not affect the results, as evidenced **by the** sensitivity analysis (**Table 6-4**) . A larger **number** of replicate points would be required for smaller spill sizes, since more points are in general necessary to give adequate resolution over smaller areas. Also, in areas and at times **when** seals are rarer, **more** seal points **would** be necessary to reduce the variability in the results. **The** Unimak Pass spill simulation is a demonstration of this phenomenon in that the results are much less variable for females than for males at a time and location when females are much more abundant.

Figure 6-4 shows how model variability changed **as** the **number** of replicate points increased, and the number of seals per point decreased. It is clear **that model** variability was reduced as the number of points increased, whereas, the mean did not vary significantly with number of replicate points above 60 replicates. **The** error associated with the mean estimated number of seals oiled decreases with increasing number of seal points and with increasing number of runs using different random number seeds. Therefore, an alternative to increasing the number of seal points for **smaller** spill events **would** be **to** increase the **number** of simulations run, i.e. to use more than 8 random number seeds.

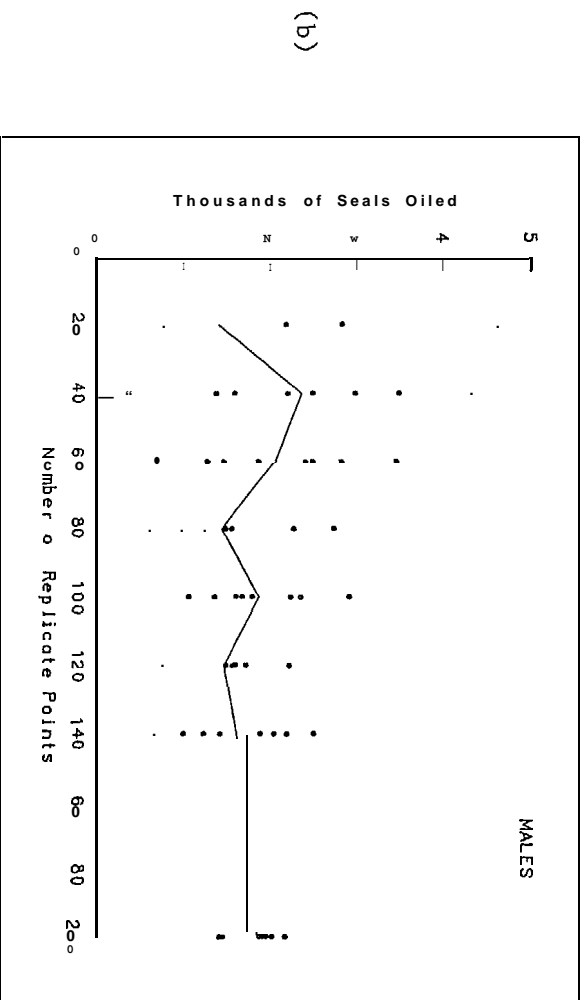
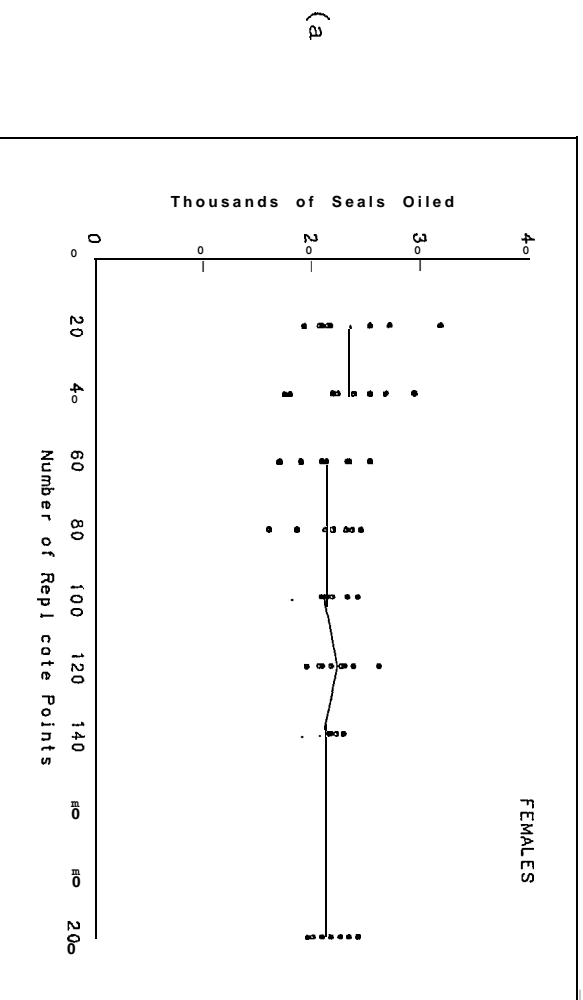


Figure 6-4. Number of seals oiled in simulations using different seed values as a function of the number of replicate points used for each seal type: (a) females, (b) males. The line connects the mean number oiled for each number of replicates.

7. **Simulation** Results

For sensitivity reasons discussed in Section 6.3, a time step of 3 hours and 60 replicate points for each of the 52 seal **types** (age, sex, sexual status), was used for all simulations **reported** in this section. The **model** has been implemented in **Fortran** 77 on both **PRIME-550** and **MicroVAX** computers. A simulation of one year's population dynamics, migration movements, and a **single** 10 day oil spill interaction scenario, requires about 1 1/2 **central** processing unit (CPU) hour on the **MicroVax** or 4 1/2 CPU hours on the **PRIME-550**. To determine long term effects, the population model is run at a 1 day time step without the migration computations, to simulate 100 years of population dynamics. This second run requires about 1/2 CPU hour **on** the MicroVAX, or 1 1/2 CPU hours **on** the PRIME-550.

7.1 Short-term Oil Spill Impacts

The numbers of **seals** from the equilibrium **population which** were oiled by the **Unimak** Pass and St. Paul spill scenarios (both considered "extreme" cases, as **&scribed** **in** section 5.2) are presented in Tables 7-1 and 7-2. Table 7-3 shows results for the St. Paul spill, but without **oiling** of seals on the adjacent rookeries, as was assumed in Table 7-2. The daily data are for the random number seed which generates numbers of oiled seals nearest to the mean of 8 runs with different seed values. In each of these runs, 100% of oiled seals were assumed to die, so no **re-oiling** of seals occurred on days subsequent to their initial encounter. Similar runs using the 1986 population, rather than the equilibrium population, are presented in **Tables** 7-4, 7-5, and 7-6.

The **Unimak** spill oiled many more females than males, oiling 2.9% and 0.5% of the population, respectively. Ninety-one percent of oiled seals were females. This is because the **Unimak** spill occurred during the peak of the migration of pregnant females to the rookeries. The St. Paul spill oiled considerably more seals, and a more even selection of age and sex classes (59% of oiled seals were females). With the assumption that all seals on the **Gorbatch** and Ardiguén rookeries were oiled by spinets which intersected the shoreline, 3.7% of the females and 4.6% of the males in the population were oiled. If seals on the rookeries were assumed **not** to be oiled, these percentages were reduced to 2.1% for females and **3.2%** for males. Many of the animals in the rookeries were pups. In general, random variability between runs was on the order of 15-25%, as **measured** by the coefficient of variation (standard deviation divided by the mean). The **Unimak** spill result for males is the **most** notable exception, and occurred because so few males were passing through the area at the time of the simulated spill.

Since mortality rates after oiling are **not** well known for fur seals, a range of assumed values was utilized: 100%, 75%, 50%, 25%. Those seals

Table 7-1. Number of seals oiled by day for the simulated **Unimak** Pass spill and an equilibrium seal population of 1.16 million seals. For the migration model, 60 replicate seal points, a time step of 3 hours, and the random number generator seed which produced a result near the mean of 8 runs were used.

Number of Seals Oiled By Day			
<u>Julian Day</u>	<u>Total</u>	<u>Females</u>	<u>Males</u>
178	271	271	0
179	7454	7454	0
180	3819	3176	643
181	90	90	0
182	972	972	0
183	1176	1176	0
184	3463	3424	39
185	5007	5007	0
186	13	0	13
TOTAL	22266	21572	694
Mean of 8 runs	23578	21519	2059
Standard deviation	3568	3028	898
Coefficient of Variation	15.1%	14. 1%	43.6%

Table 7-2. Number of seals oiled by day for the simulated St. Paul spill and an equilibrium population of 1.16 million seals. All seals on the **Gorbatch** and Ardiguén rookeries during the spill, simulation are assumed to be oiled. For the migration model, 60 replicate seal points, a time step of 3 hours, and the random number generator seed **which** produced a result near the mean of 8 runs were used.

Number of Seals Oiled By Day			
<u>Julian Day</u>	<u>Total</u>	<u>Females</u>	<u>Males</u>
183	5015	4317	698
184	2380	2247	133
185	3048	2071	977
186	4672	1331	3341
187	4736	2570	2166
188	5237	3799	1438
189	4140	2512	1628
190	3798	2129	1670
191	5230	4012	1218
192	3251	1914	1337
193	1787	1469	317
TOTAL	43294	28370	14924
Mean of 8 Runs	46669	27539	19130
Standard Deviation	4994	4191	2554
Coefficient of Variation	10.7%	15.2%	13.4%

Table 7-3. Number of seals oiled by day for the **simulated** St. Paul spill and an equilibrium population **of** 1.16 million seals. Seals on **the Gorbatch** and Ardiguen rookeries are assumed not to **be** oiled unless they leave land to feed and swim through oil en route to the feeding area. For the migraton model, 60 replicate seal points, a time step of 3 hours, and the random number generator seed which produced a result near the mean of 8 runs were used.

Number of Seals Oiled By Day			
<u>Julian Day</u>	<u>Total</u>	<u>Females</u>	<u>Males</u>
185	156	64	93
186	1363	424	939
187	4182	2149	2031
188	3603	3409	194
189	1227	301	926
190	2691	1589	1103
191	4397	4079	318
192	4129	1712	2417
193	2838	1228	1610
TOTAL	24586	14954	9632
Mean of 8 Runs	28868	15342	13526
Standard Deviation	5784	3939	3266
Coefficient of Variation	20.0%	25.7%	24.1%

Table 7-4. Number of seals oiled by day for the simulated Unimak Pass spill and the 1986 seal population of 739 thousand seals. For the migration model, 60 replicate seal points, a time step of 3 hours, and the same random number generator seed used in Table 7-1 were used.

Number of Seals Oiled By Day			
<u>Julian Day</u>	<u>Total</u>	<u>Females</u>	<u>Males</u>
178	1112	1112	0
179	5541	5057	439
180	1823	1823	0
181	515	418	97
183	786	786	0
184	1522	1522	0
185	3285	3014	271
TOTAL	14583	13731	852
Mean of 8 Runs	14235	13449	786
Standard Deviation	1400	1632	330
Coefficient of Variation	9.8%	12.1%	42.0%

Table 7-5. Number of seals oiled by day for the simulated St. Paul **spill** and the 1986 seal population of 739 thousand seals. All seals in the **Gorbatch** and Ardiguén rookeries during the **10 day spill** simulation are assumed to be oiled. For the migration model, 60 replicate seal points, a time step of 3 hours, and the same random number generator seed used in Table 7-2 were used.

Number of Seals Oiled By Day			
<u>Julian Day</u>	<u>Total</u>	<u>Females</u>	<u>Males</u>
183	4071	2347	1724
184	1596	1043	554
185	2346	1085	1261
186	3624	1426	2198
187	3137	1019	2118
188	3422	2713	709
189	2251	2160	91
190	3998	2637	1361
191	2955	1242	1713
192	3200	2171	1029
193	2038	1666	372
TOTAL	32639	19509	13130
Mean of 8 Runs	30725	17294	13430
Standard Deviation	2130	1483	1351
Coefficient of Variation	6.9%	8.6%	10.1%

Table 7-6. Number **of** seals oiled by day for the simulated St. **Paul** spill and **the** 1986 seal population of 739 thousand seals. Seals on the **Gorbatch** and Ardiguén rookeries are assumed not to be oiled unless they leave land to feed and swim through oil en route to the feeding area. For the migration model, 60 replicate seal points, a time step of 3 hours, and the same random number generator seed used-in Table 7-3 were used.

Number of Seals Oiled By Day			
<u>Julian Day</u>	<u>Total</u>	<u>Females</u>	<u>Males</u>
184	51	51	0
185	353	327	26
186	2096	1615	481
187	1945	1176	769
188	2409	2044	365
189	2105	878	1227
190	1401	965	436
191	1874	1419	455
192	1004	537	467
193	1498	312	1186
TOTAL.	14737	9325	5412
Mean of 8 Runs"	16749	9334	7416
Standard Deviation	2170	779	2387
Coefficient of Variation	13.0%	8.3%	32.2%

not **dying** from oiling were assumed to recover completely. If they were **re-oiled** later, their probability Of **mortality** at **that time was assumed** the same as before. **This** means that, to the extent that seal points encounter **oil** more than once, the 50% mortality rate results in **a** net mortality greater than one half that at 100% mortality.

Table 7-7 shows the number of seals oiled, and the number subsequently dying as the result of oiling, for each scenario and mortality rate. In the **Unimak** Pass spill simulation, seals were migrating through the area and therefore, were only oiled once as they passed by. **II-N-Is**, the number of seals killed **is** proportional to the assumed mortality rate. However, in the St. Paul spill simulations, some seal points were oiled more than once since they **moved** on and off the rookeries repeatedly and, in the case in which seals on the rookeries were oiled, since they remained on land for more than one day. In these cases, the effect assuming a 25% **mortality** rate was **much** larger than 1/4 that assuming 100% mortality.

The **numbers** of seals remaining **alive** after **each** spill scenario are given in Table 7-8. In each simulation, the difference between the oil-affected and non-affected population on December 31 was larger than the number of seals killed during the spill itself. This was due to the fact that pregnant seals oiled did not give birth to pups, **and** the pups of lactating seals which died, died as well. The effect of the **Unimak** spill was as high as **the** St. Paul spill since many of the oiled females were pregnant in the **Unimak** case. The reduction **in** males by **the** end of the year after the **Unimak** spill was due mostly to the loss of that year's pups, while females of all ages were killed in the simulation,

Since the number of seals lost due to oiling was a small percentage of the population, plots of numbers versus time of the oil-affected compared to the non-affected population are difficult to distinguish. Thus, the results are plotted as the difference between the spill-affected populations and the standard equilibrium or 1986 populations for **the** year of the **spill** (Figures 7-1 to 7-6). The differences diminish with time after the spill as some seals which were oiled in the affected population died anyway in the standard populations.

The number of seals oiled in the 1986 population simulations was close to 63% of the number **oiled** in the equilibrium population. **Thus**, the number of seals oiled **by** a given spill simulation is approximately proportional to population size. Therefore, the results in Tables 7-1 to 7-6 and Figures 7-1 to 7-6 **may** be scaled **to** other population sizes, assuming the sex and age structure is similar.

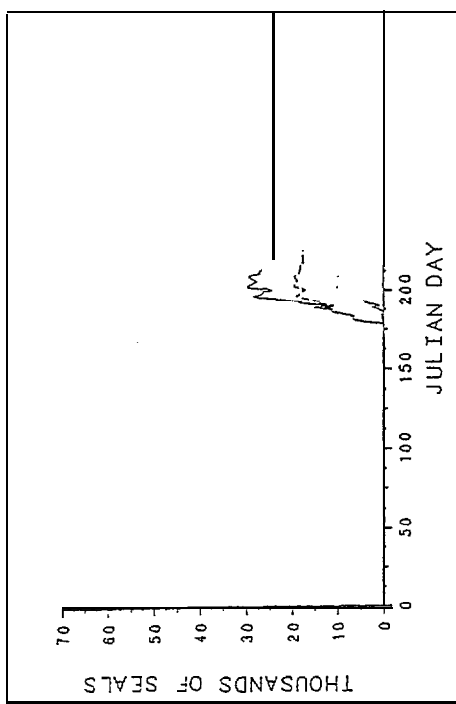
The percentage of the non-affected equilibrium population of 1,16 million seals which dies from natural causes each year is **16%** for females and 29% for males. For the 1986 population with continued entanglement, mortality **due to natural causes** plus entanglement is **18%** of the females and 32% of the **males** over 1 year. In comparison, the spill scenarios reported here would be expected to oil and kill up to 4% of the

Table 7-7. Numbers of seals oiled and subsequently dying as the result of oiling (killed in parentheses) in simulated oil spills near **Unimak** Pass and St. Paul Island assuming various percent mortalities for oiled seals. For cases where mortality rate was less than 100%, the number of seals oiled included those which had been oiled on previous days. The number of different seals which saw oil one or more times is listed for the 100% mortality case.

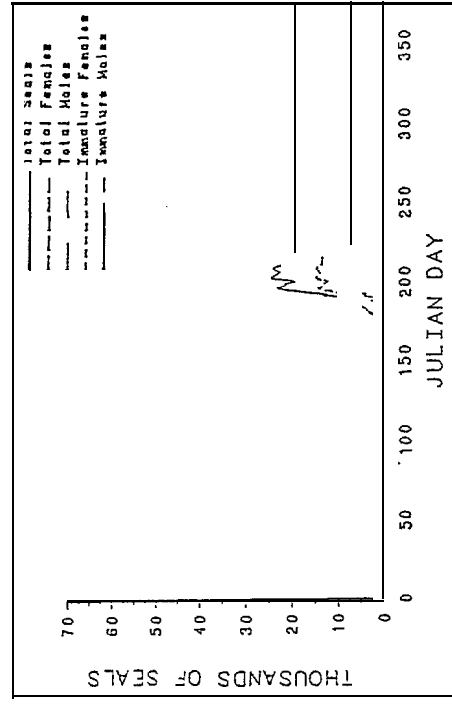
Initial Population	% Mortality Once Oiled	Unimak Pass		St. Paul (Oiled on Rookeries)		St. Paul (Not Oiled on Rookeries)	
		Females	Males	Females	Males	Females	Male
Equilibrium population of 1163 thousand seals	100	21519 (21519)	2059 (2059)	27539 (27539)	19130 (19130)	15342 (15342)	1352 (1352)
	75	20737 (15553)	1130 (848)	33399 (2504)	20813 (15610)	16317 (12238)	1121 (841)
	50	20751 (10376)	1130 (565)	41613 (20807)	23828 (11914)	16456 (8228)	1151 (575)
	25	20766 (5194)	1130 (786)	58148 (17294)	29551 (13430)	16594 (9334)	1189 (741)
	100	13449 (13449)	786 (786)	17294 (17294)	13430 (13430)	9334 (9334)	741 (741)
1986 population of 693 thousand seals	75	16192 (12685)	1929 (1447)	20360 (15270)	17365 (13024)	12302 (9227)	934 (701)
	50	17036 (8518)	1929 (965)	25806 (12903)	20960 (10480)	12788 (6394)	948 (474)
	25	17161 (4290)	1929 (482)	37118 (9280)	28235 (7059)	13287 (3322)	962 (240)

Table 7-8. Remaining population of **seals** following simulated **oil spills** near **Unimak** Pass and St. Paul **Island** assuming various percent mortalities for oiled seals. The numbers in parentheses are the difference between the non-impacted (0% mortality) and impacted population. (**Timestep** - 3 hours, 60 replicate seal points, mean random number generator seed.)

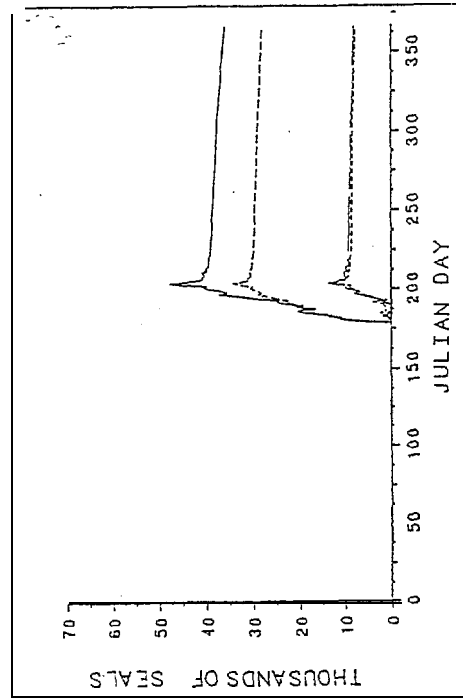
Initial Population	% Mortality Once Oiled	Thousands of seals alive on Dec. 31					
		Unimak Pass		St. Paul (Oiled on Rookeries)		St. Paul (Not oiled on Rookeries)	
		Females	Males	Females	Males	Females	Males
Equilibrium population of 1163 thousand seals and no entanglement	100	717 (28)	409 (9)	711 (34)	397 (21)	725 (20)	404 (14)
	75	724 (21)	410 (8)	718 (27)	398 (20)	730 (15)	407 (11)
	50	728 (17)	410 (8)	723 (22)	403 (15)	735 (10)	410 (8)
	25	733 (12)	410 (8)	730 (15)	409 (9)	740 (5)	413 (5)
	0	745	418	745	418	745	418
1986 population of 693 thousand seals and with entanglement	100	428 (17)	242 (6)	421 (24)	230 (18)	434 (11)	240 (8)
	75	428 (17)	241 (7)	428 (17)	233 (15)	435 (10)	240 (8)
	50	432 (13)	241 (7)	431 (14)	235 (12)	438 (7)	242 (6)
	25	436 (9)	241 (7)	436 (9)	240 (8)	442 (3)	245 (3)
	0	445	248	445	248	445	248



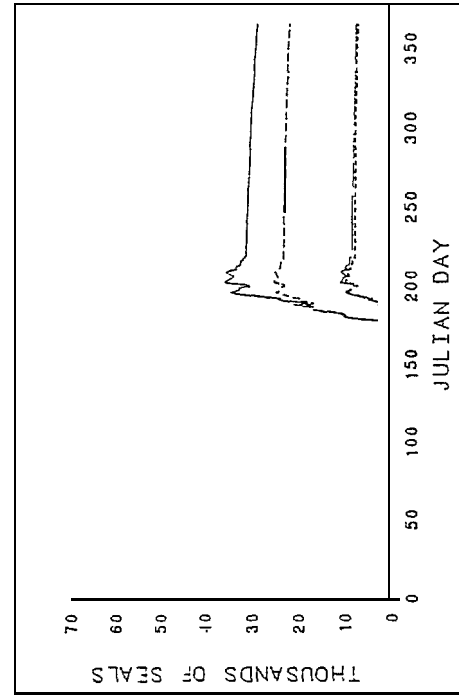
(c)



d)



(a)



(b)

Figure 7- Difference between non-affected equilibrium population and affected population during the year of the simulated Unimak Pass spill, assuming (a) 10%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates.

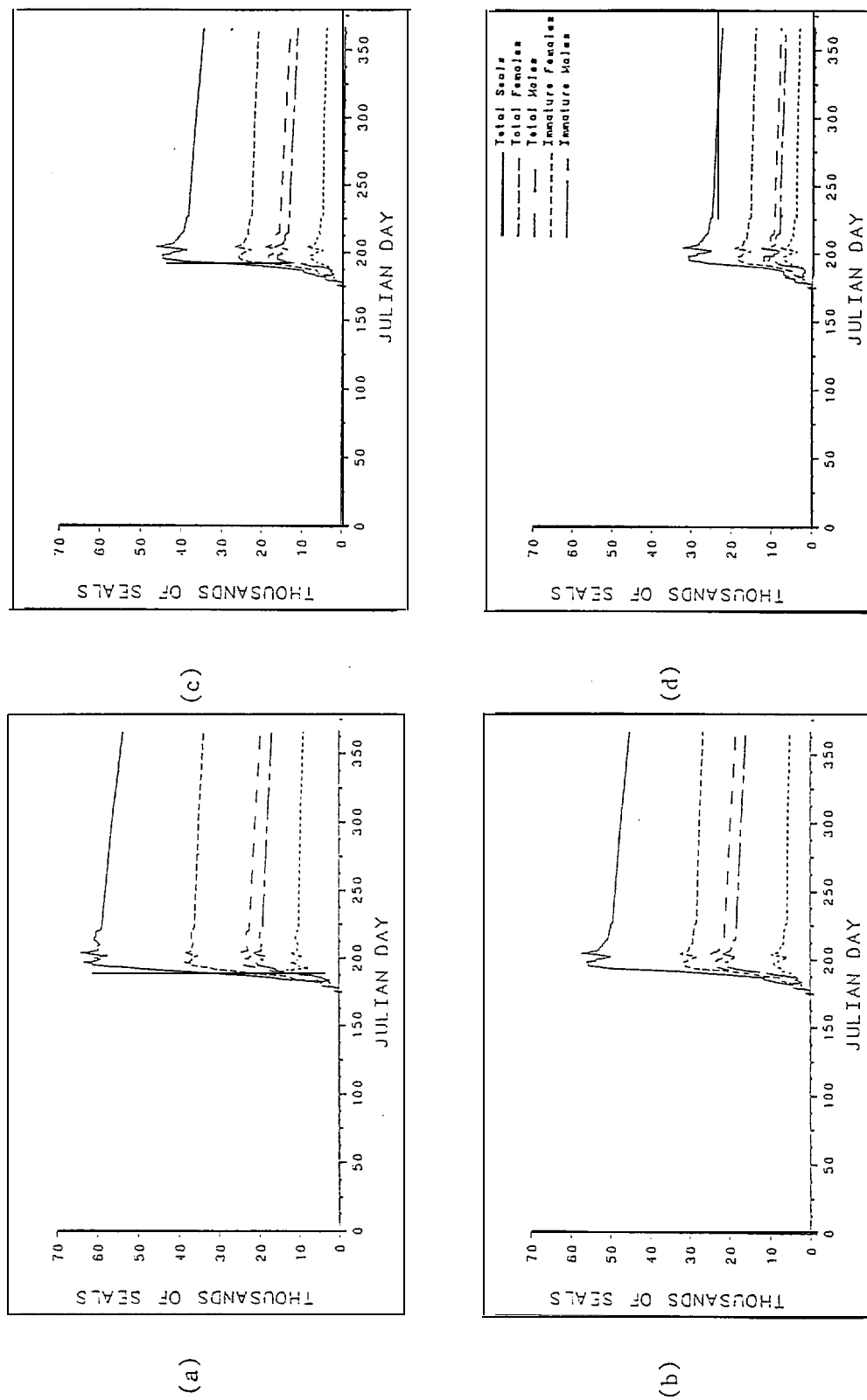


Figure 7-2. Differences between non-affected equilibrium and affected populations during the year of the simulated St. Paul spill, assuming seals on land where oil comes ashore are oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates.

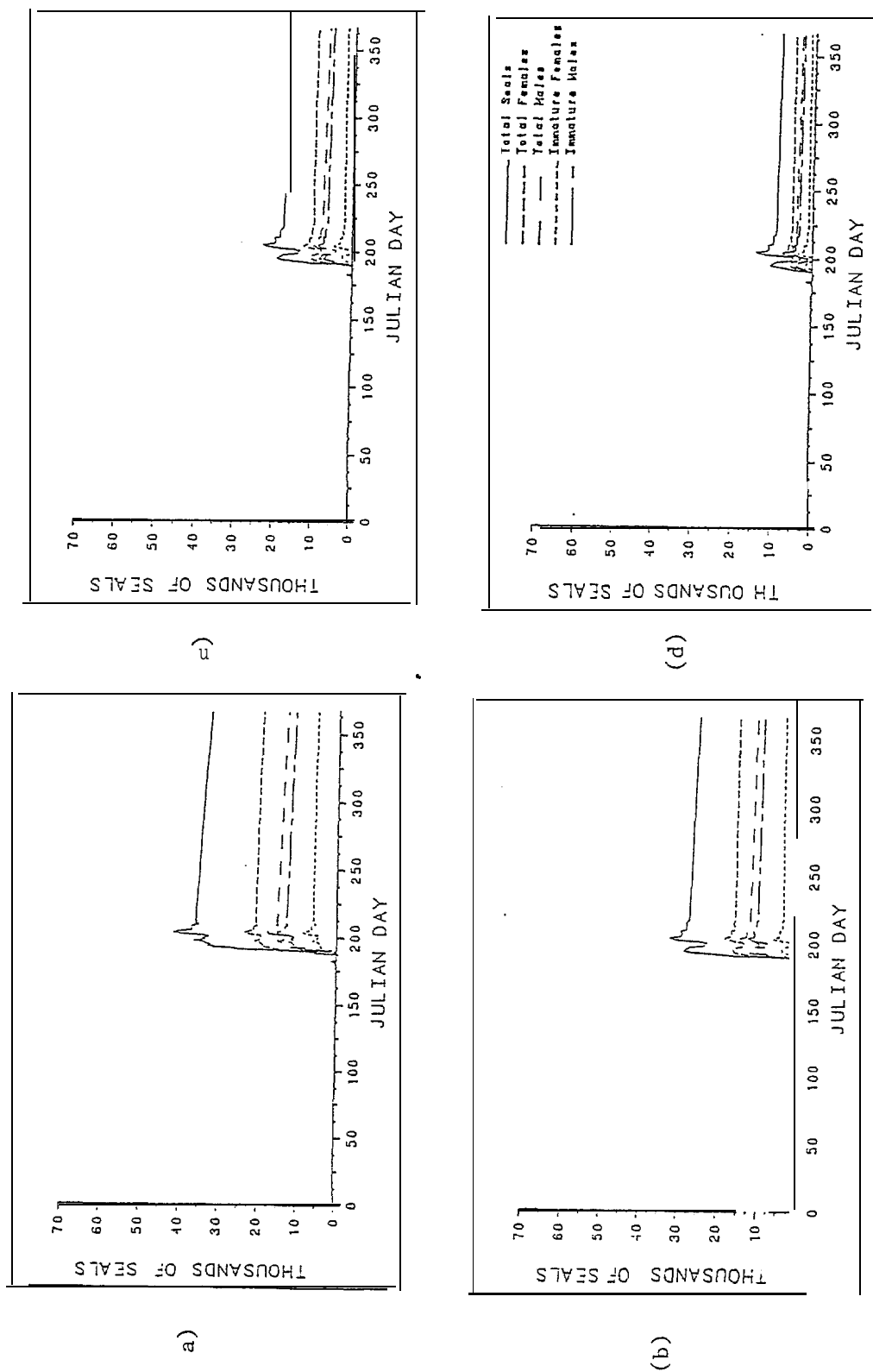


Figure 7-3. Difference between non-affected equilibrium and affected populations during the year of the simulated St. Paul spill, assuming seals on land where oil comes ashore are not oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates.

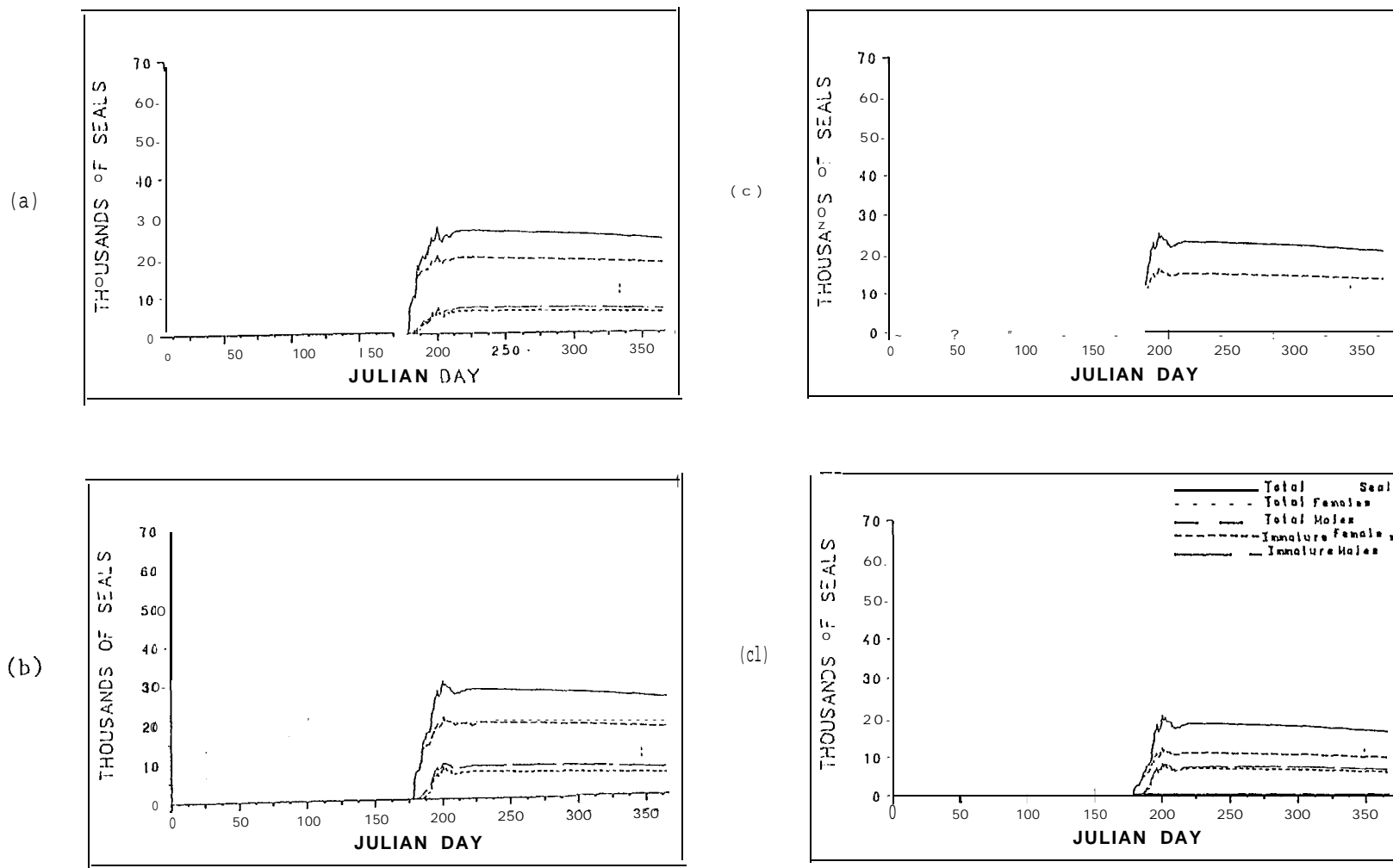
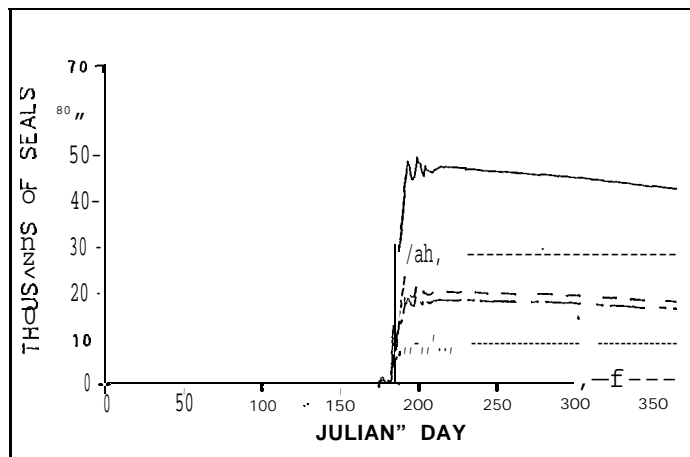
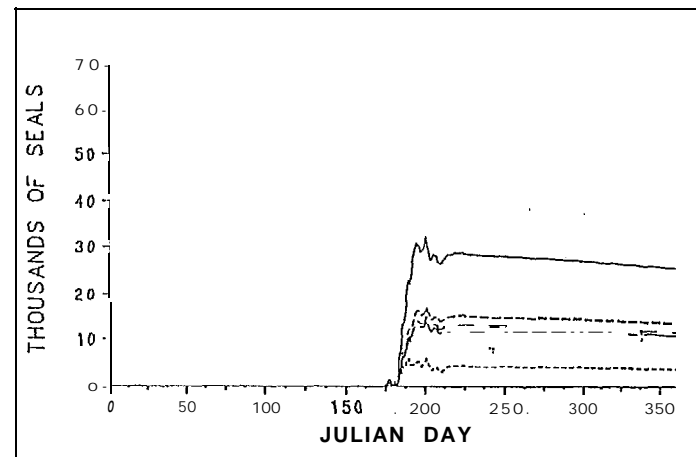


Figure 7-4. Difference between non-affected 1986 population and affected population during the year of the simulated Unimak Pass spill, assuming (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates.

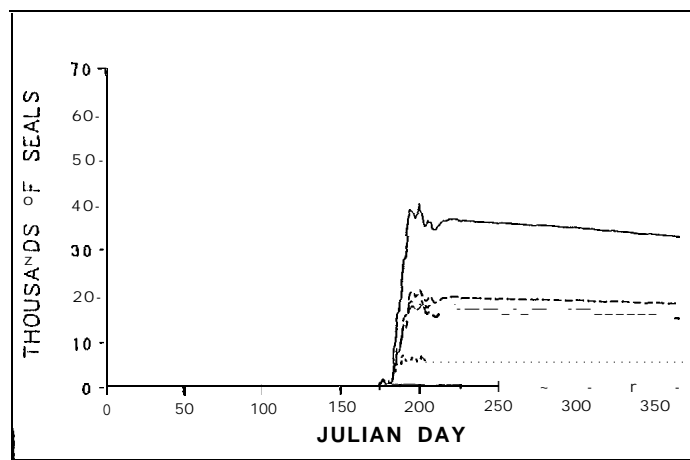
(a)



(c)



(b)



(d)

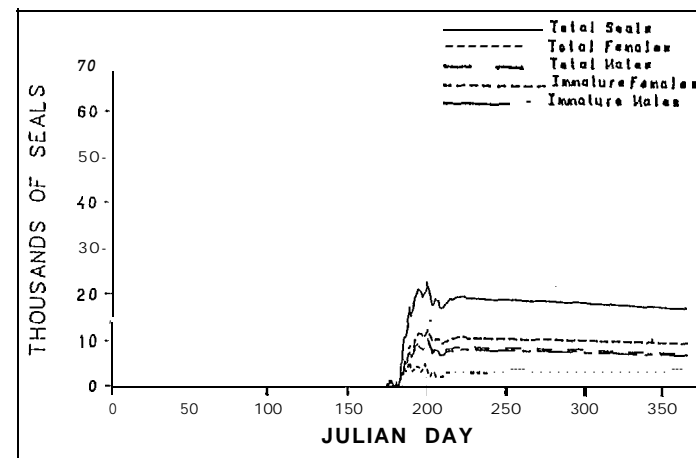


Figure 7-5. Difference between non-affected 1986 population and affected population during the year of the simulated St. Paul spill, assuming seals on land maybe oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates.

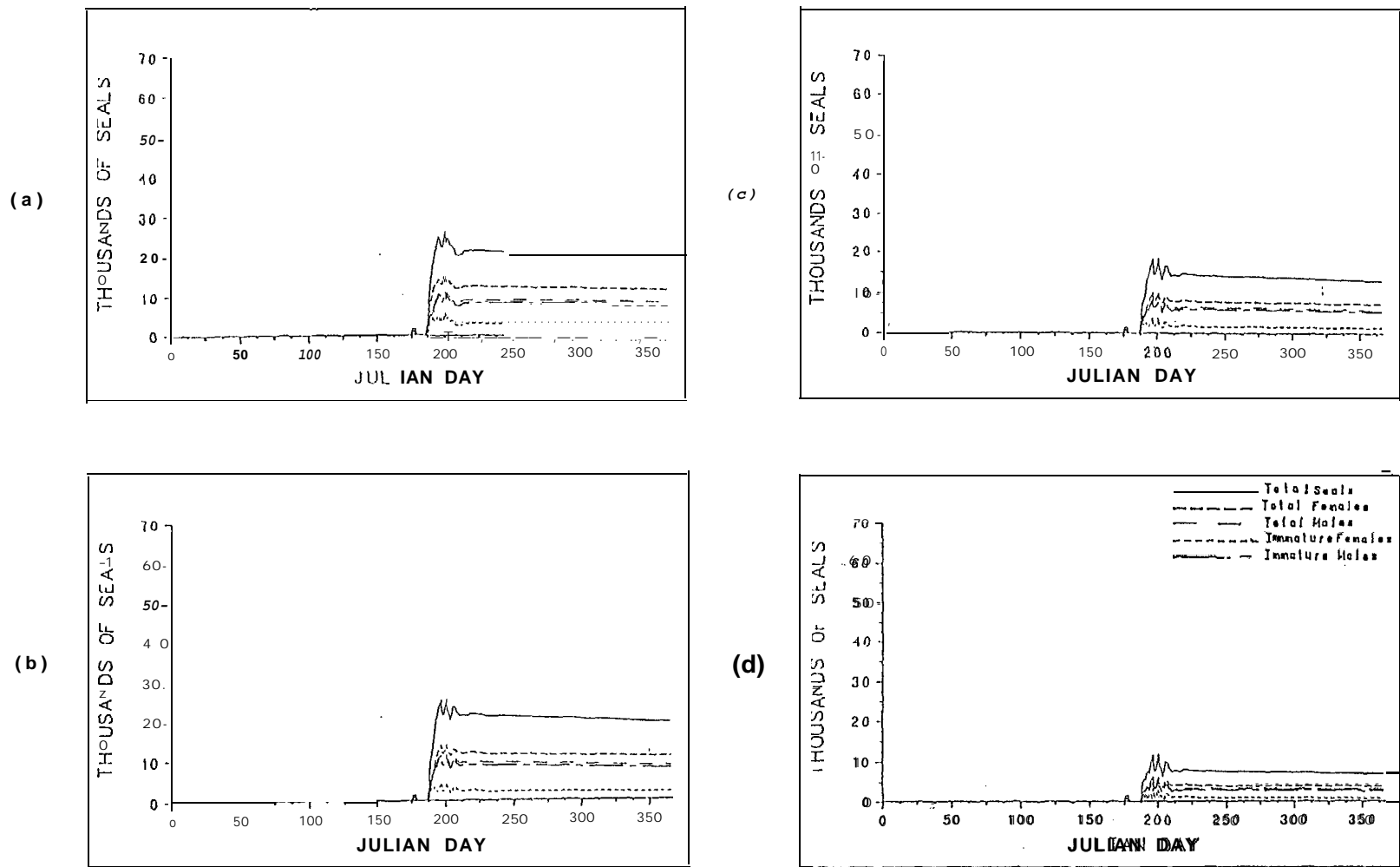


Figure 7-6. Difference between non-affected 1986 population and affected population during the year of the simulated St. Paul spill, assuming seals on land are not oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates.

population, some of which (up to 1/6 of those killed) would have "died of natural causes by the end of the year. Since the number of seals oiled by a given oil spill simulation is approximately proportional to population size, these percentages would be similar at other population sizes, assuming a similar age and sex structure,

7.2 Long-term Population Responses

Figures 7-7 through 7-12 show the recoveries of oil-affected populations by plotting the differences between the oil-affected population and the reference standard, non-affected population. In the case of the equilibrium population, entanglement mortality was assumed to remain at zero both before and after the spill. For the oil-affected 1986 populations, entanglement mortality was assumed to continue at present rates.

Recovery was considered complete when the difference between oil-affected and non-affected populations was less than a specified percentage of the non-affected population size. Since pup counts in the field are accurate to the nearest 100 animals (e.g., Kozloff, 1985) and population estimates are based on these counts, field estimates of population numbers are probably only accurate to the nearest 1000 seals. Differences of less than 1000 seals certainly would not be measurable. We have therefore used 0.1% as a "complete" recovery measure, and 1% as a second "effective" recovery measure which could more reasonably be field verified.

For the oil-affected equilibrium populations (Figures 7-7, 7-8 and 7-9), recovery to the 0.1% difference level occurred after about 20-30 years; recovery to the 1% level was achieved after about 5-20 years had passed. For the smallest perturbation simulated here, (Figure 7-9d) fewer than 1% of the population died in the simulation. In all cases, (Figure 7-7 through 7-12) recovery was very rapid immediately following a perturbation, with the recovery rate decreasing as the affected population neared the non-affected population level.

For the oil-affected 1986 populations, where entanglement was assumed to continue at present levels (Figures 7-10, 7-11 and 7-12), recovery was slower than for the equilibrium population, requiring about 60 years to reach the 0.1% difference level and up to 25 years to reach the 1% difference level, with the smallest perturbation being less than 1% of the population killed (Figure 7-12d). The slower recovery is due to the additional effect of entanglement-induced mortality. The decline due to entanglement mortality was much more significant than that due to oil spill effects in these simulations.

The Unimak spill recovery involved more age structure adjustment than the St. Paul case, and therefore resulted in more oscillation. It has been shown that twice the mean reproductive age determines the period of major oscillations in population numbers, the amplitude of the

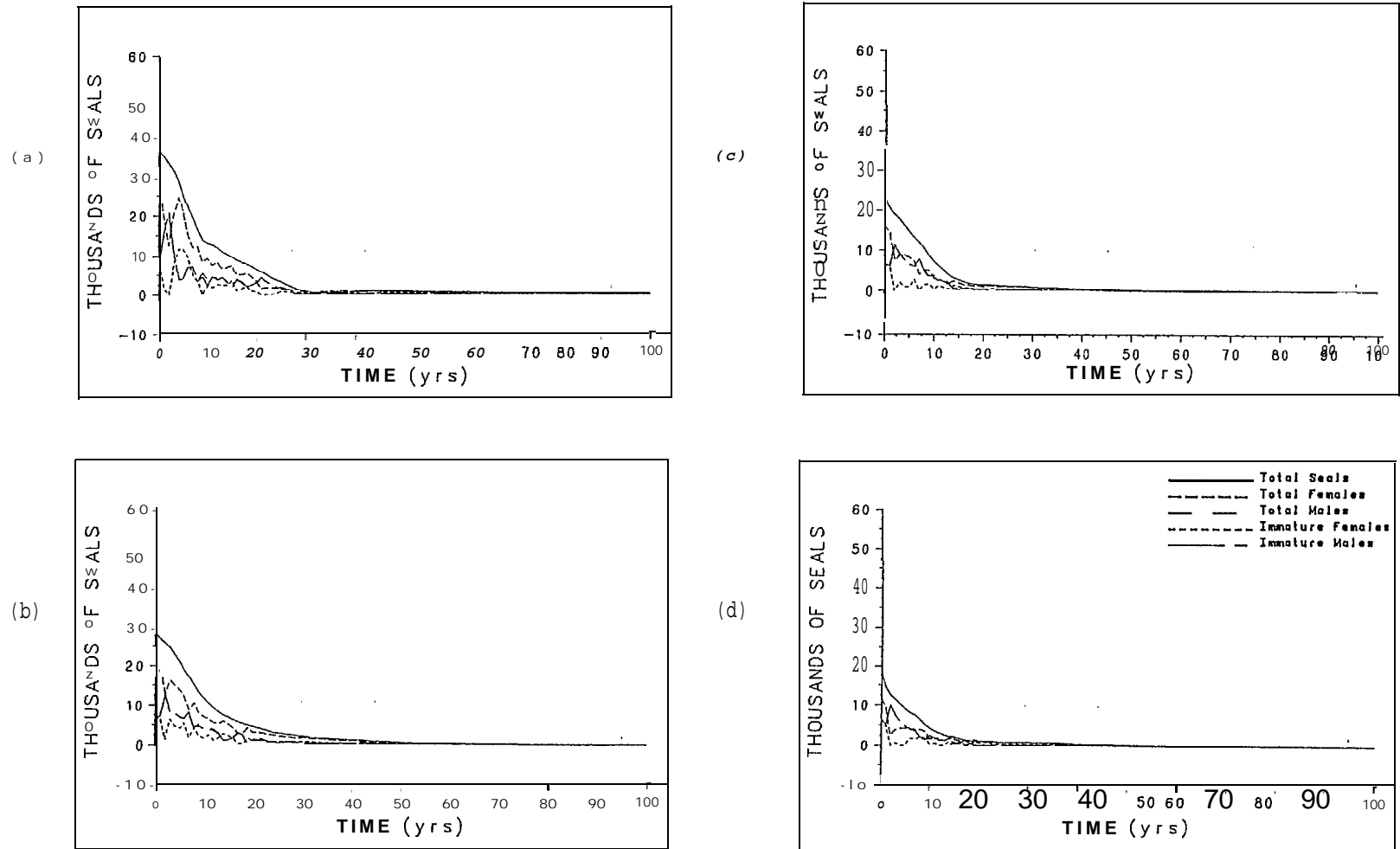


Figure 7-7. Recovery of the equilibrium population from the simulated effect of the Unimak Pass spill assuming (a) 100%, (b) 75%, (c) 50%, (d) 25% oil induced mortality rates. Plotted is the difference between non-affected and affected populations,

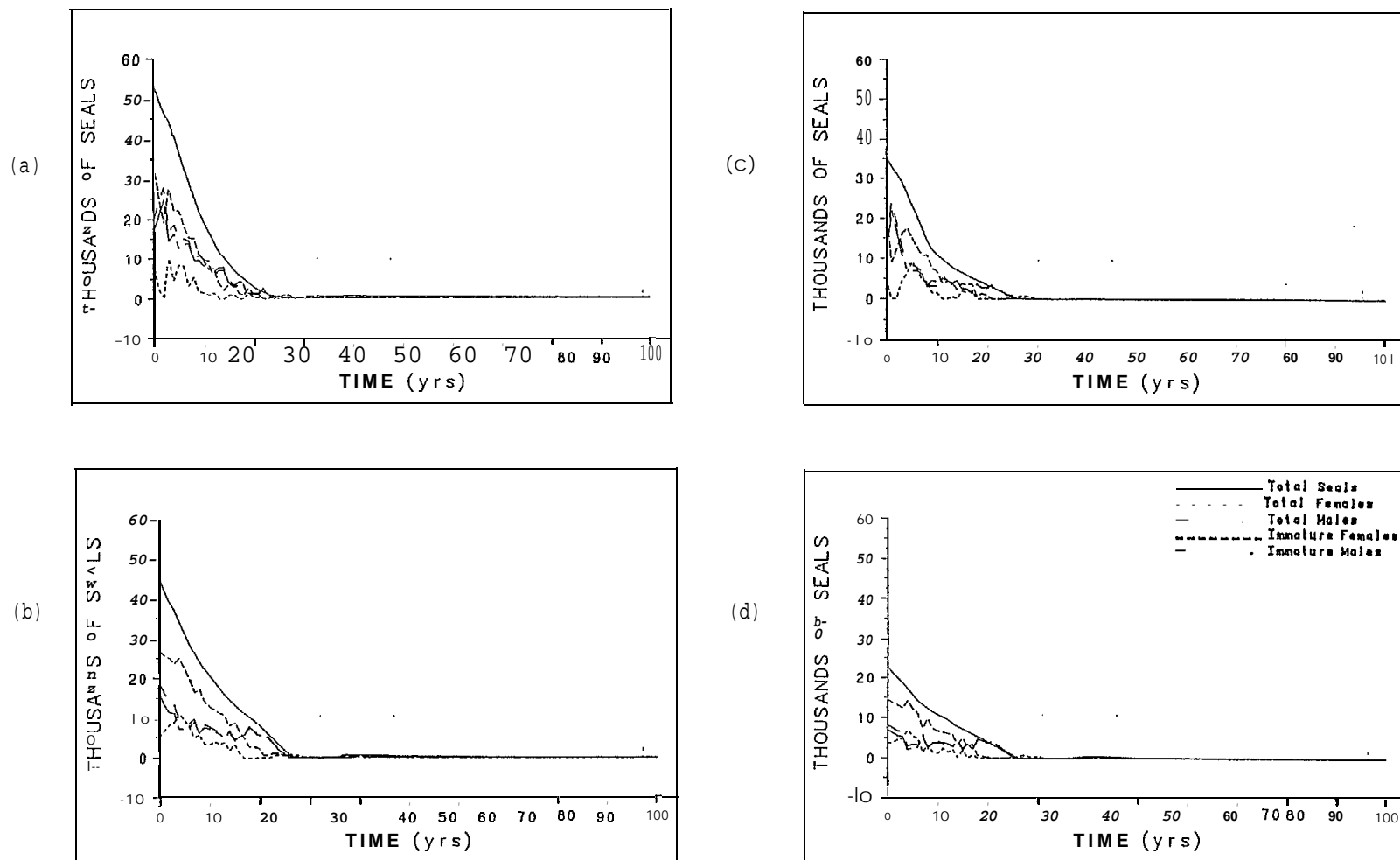
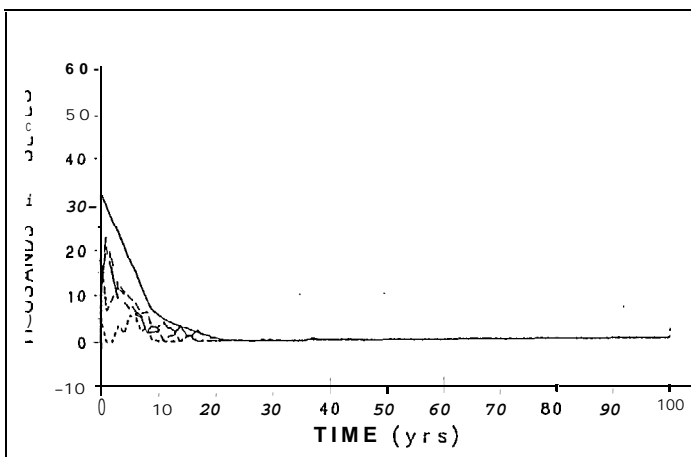
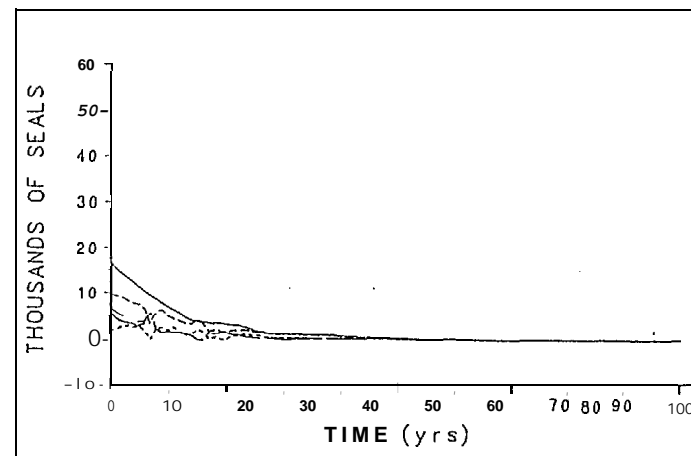


Figure 7-8. Recovery of the equilibrium population from the simulated effect of the St. Paul spill, assuming seals on rookeries where oil comes ashore are oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates. Plotted is the difference between non-affected and affected populations.

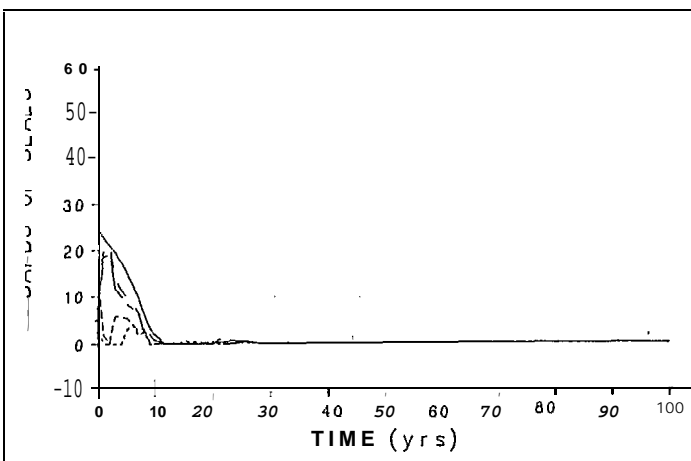
(a)



(c)



(b)



(d)

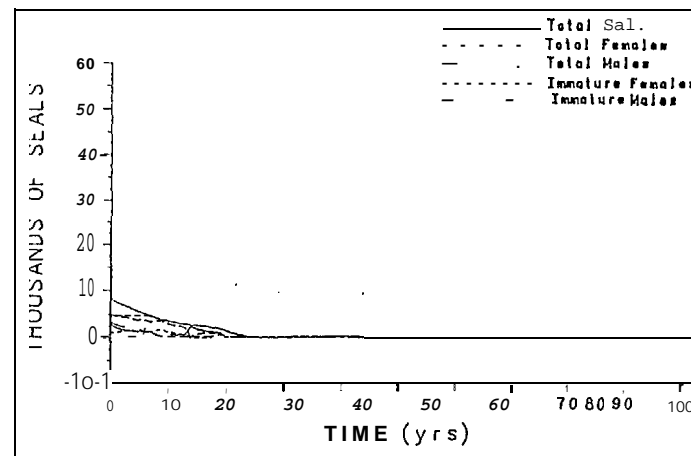
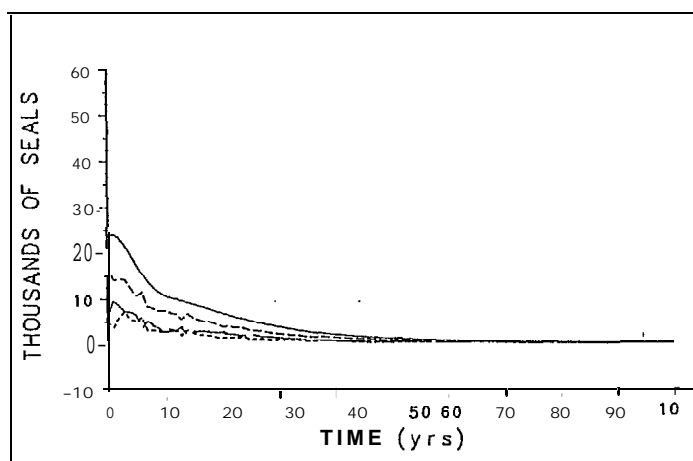
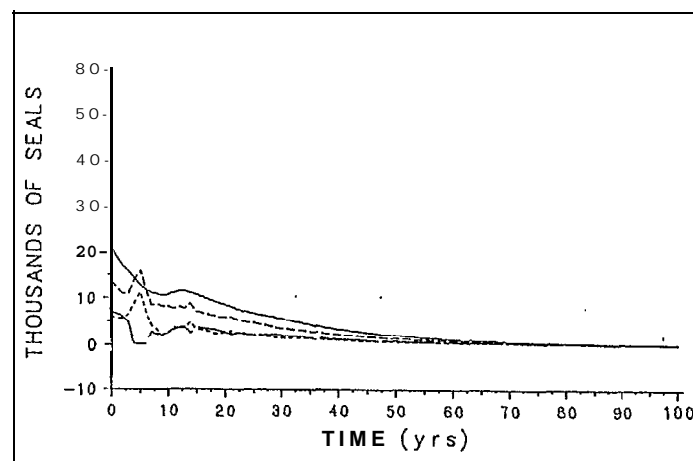


Figure 7-9. Recovery of the equilibrium population from the simulated effect of the St. Paul spill, assuming seals on rookeries where oil comes ashore are not oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates. Plotted is the difference between non-affected and affected populations.

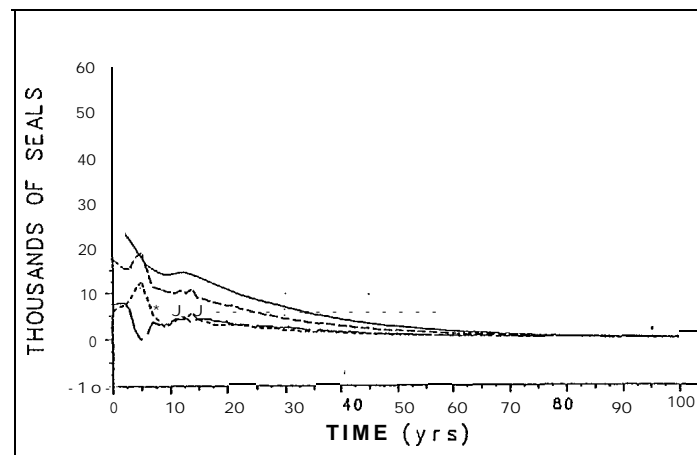
(a)



(c)



(b)



(d)

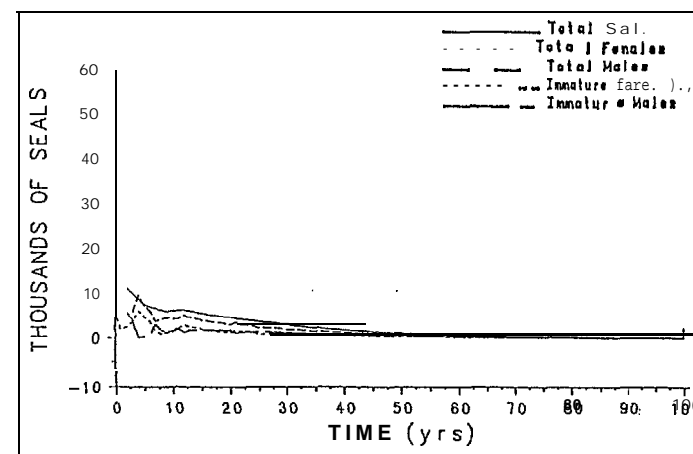


Figure 7-10. Recovery of the 1986 population from the simulated effect of the Unimak Pass spill, assuming present rate of decline, and (a) 100%, (b) 75% (c) 50%, (d) 25% oil-induced mortality rate. Plotted is the difference between non-affected and affected populations.

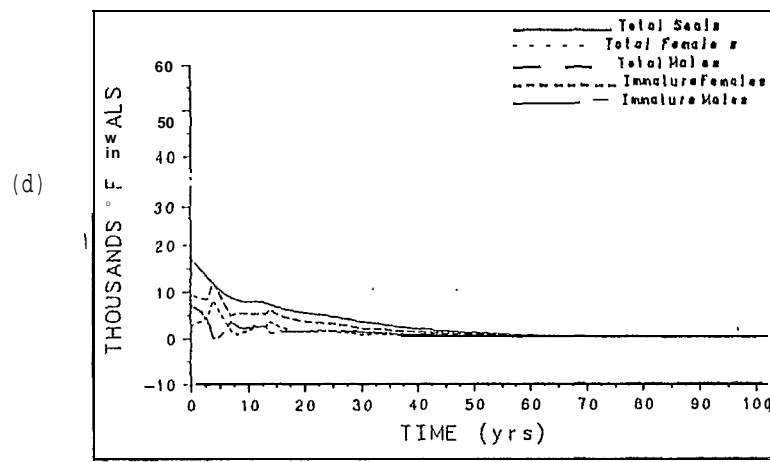
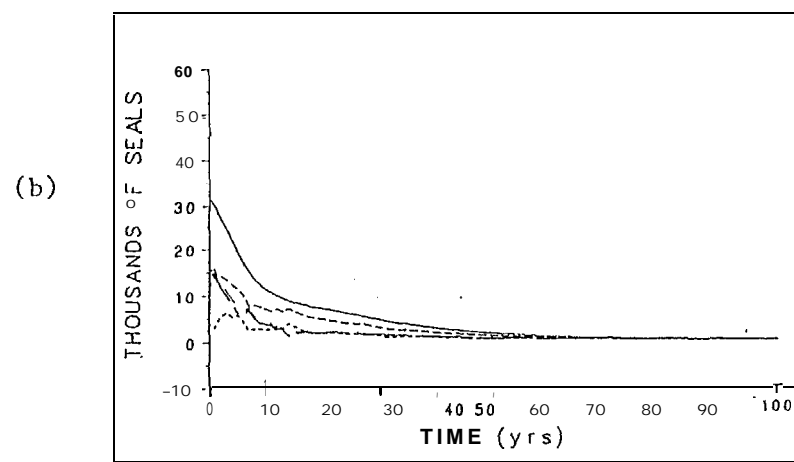
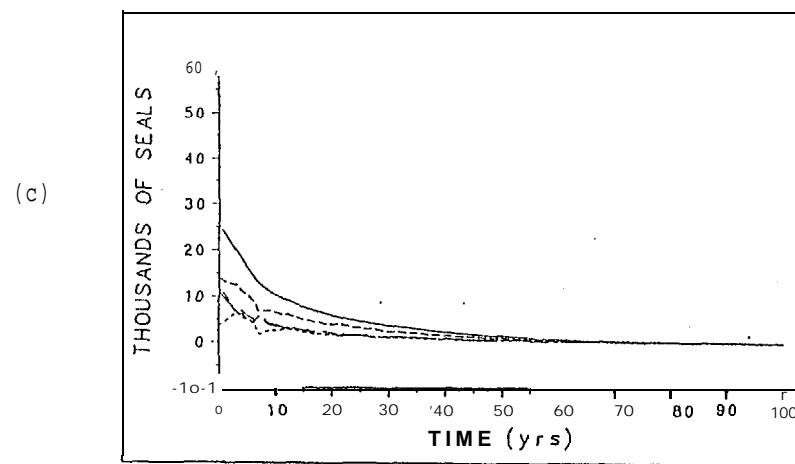
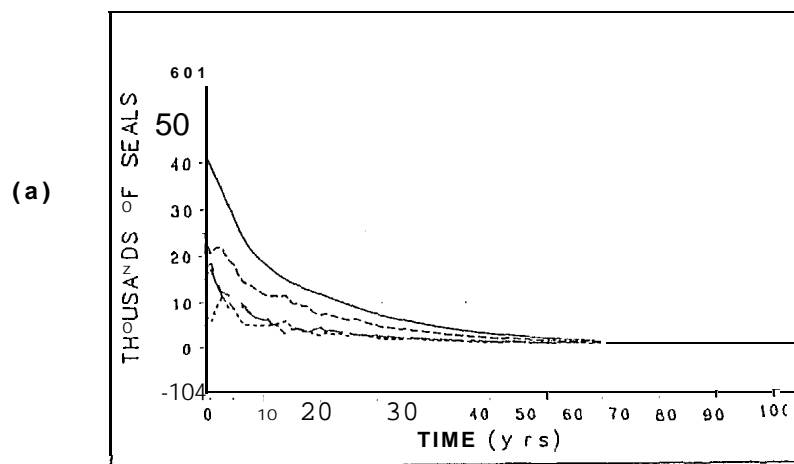


Figure 7-11, Recovery of the 1986 population from the simulated effect of the St. Paul spill, assuming present rate of decline, seals on rookeries where oil comes ashore are oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates. Plotted is the difference between non-affected and affected populations.

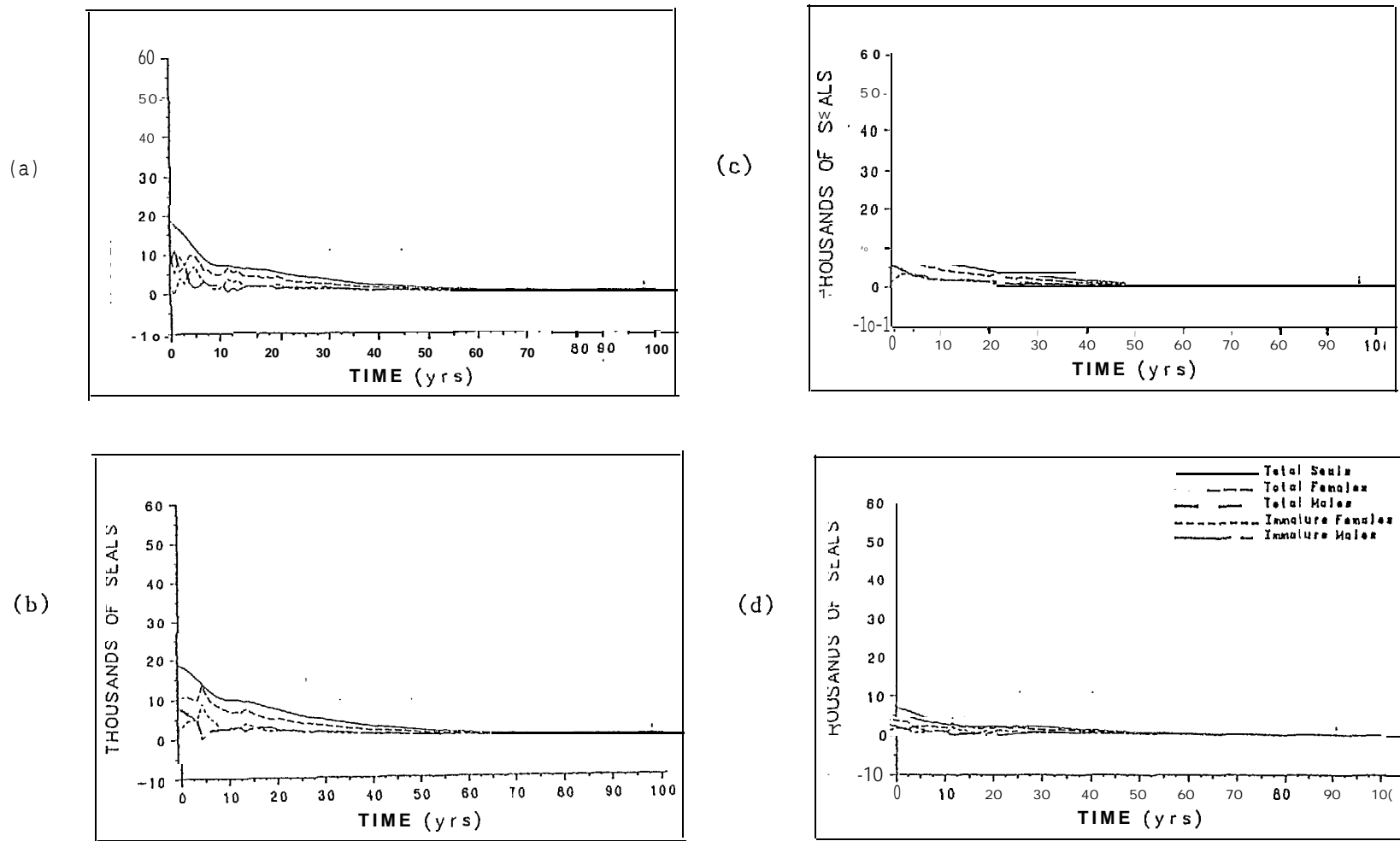


Figure 7-12. Recovery of the 1986 population from the simulated effect of the St. Paul spill, assuming present rate of decline, seal rookeries where oil comes ashore are not oiled, and (a) 100%, (b) 75%, (c) 50%, (d) 25% oil-induced mortality rates. Plotted is the difference between non-affected and, affected populations.

oscillations being proportional **to** the age at first reproduction (Allen and **Basasibwaki**, 1974) . The extent to which this is true decreases when additional sources of periodicity are included in the system, and when reproduction does not occur instantaneously, but is distributed over a finite period of time (Reed and **Spaulding**, 1984). The mean reproductive age for female fur seals, i.e., the average age in the distribution of number of pregnant seals by age from Tables 4-1 and 4-2, in the model is about **11** years. Regular major oscillations cannot be detected in the simulations in Figures 7-7 to 7-12. However, twenty-three **year** oscillations are clearly seen in **the** simulation of **the** 1950s population (Figure 4-8b, c, and d).

In these recovery simulations following oil spills, the ratio of female to **male** juvenile survival to age 2 was assumed to be 1.0. To the extent that this ratio is higher than 1.0, the recovery rate will be faster, and, based on the results here, major (22 or 23 year) oscillations will be induced in the population as it approaches the **new** equilibrium. Since recovery from perturbation at equilibrium is about twice as fast when assuming a ratio to age 2 of 1.6 instead of 1.0 (Figure 6-1 and 6-2), recovery from these oil spill scenarios would also take about half the times given above if the female to male juvenile **survival** ratio were as high as 1.6 at lower population sizes. However, very little direct evidence exists regarding the ratio of female to male juvenile survival (Chapman 1964, providing the only data) and that evidence was based on **observations** made during the 1950s when the fur seal population was at its maximum. It is **not** known what the value of that ratio is in the present population.

8. Summary of **Model** Assumptions and Conclusions

8.1 **Assumptions**

The following assumptions were incorporated into the model system:

(A) Fur seal population dynamics

1. Age specific pregnancy rates are as reported **by** York (1979, Table 4-1, Figure 4-1).
2. Birth occurs at time of arrival on the **Pribilof** Islands, and is timed to correspond to the birth distribution observed by Bartholomew and Heel (1953, Figure 4-9). The sex ratio at birth is assumed **1:1**.
3. Natural mortality rates for all seals older than two years are sex/age specific and constant, taken from **Lander** (1980a, 1981, Table 4-1, Figure 4-2).
4. Natural mortality rates of pups on land are **density** dependent, according to the data **of** Lander (1979) and the relationship derived by **Swartzman** (1984, Figure 4-3, Table 4-6).
5. Natural mortality rates of juveniles (first winter at sea at 2 years of age) are proportional to the density dependent mortality rate they suffered as pups, using **the** relationship **&rived** for males by Lander (1979) and **Eberhardt** (1981), as in Figure 4-4 and Table 4-6. Female juveniles are assumed to suffer the same mortality rates as males.
6. Harvest rates of immature males are as in **Lander** (1980a, Table 4-1, Figure 4-2).
7. The equilibrium population distribution of **1.16** million seals resulting from a simulation of **300** years is assumed **to** represent the present population in steady-state after removal of entanglement mortality. This population is nearly equivalent to the 1979 observed population.
8. To simulate the current fur seal population with entanglement at current rates, the equilibrium population was run with entanglement **mortality** to simulate the years 1979-1986, and **the** 1986 population was used in oil spill runs with entanglement. For simulations with entanglement, an added density independent mortality rate, assumed to be due to entanglement, of 0.15 per year is applied (additively) to fur **seals** up to 2 years of age. For 2 to 3 year **olds**, the added rate **is** 0.049 per year (**Fowler, 1985b**) . This latter rate is also applied to seals older than 3

years, since this results in model behavior which closely reflects the presently observed decline in population **numbers** (Table 4-4).

9. A **time** step of 1 day is used in calculating population **dynamics** (mortality, birth, and change of sexual status). Thus, changes in status are assumed to occur on a daily basis.

(B) Fur seal migration and feeding distribution

1. Between January **1** and May 1, all fur seals are south of the Aleutian Island chain.
2. Seals enter the **Bering** Sea only through **Unimak** Pass.
3. Adult females (whether pregnant or not) enter the Bering Sea through **Unimak** Pass in time to arrive at the **Pribilofs** according to the observed birth distribution (Figure 4-9). They apparently require about 2 weeks (14 days) to cross the **Bering** Sea to **their** rookeries, based on the observed peak migration through **Unimak** Pass as analyzed by **Kajimura** (1980) and **Bigg** (1982). Thus, they are assumed to swim at **40 km/day \pm 10%**. Other female **age groups** are lagged behind the adult **females** according to **suggested peak** passage times as follows: 3 year **olds**, 4 weeks after; 2 year **olds**, 7 weeks after; yearlings, 10 weeks after. These females also are assumed to swim 40 km/day,
4. Adult males enter the Bering Sea in time to arrive on the rookeries according to bull counts reported by Peterson (1965, Figure 4-9). They also are assumed to cross the Bering Sea in two weeks at **40 km/day \pm 10%**.
5. Immature males enter the Bering Sea two weeks before their observed arrival on the rookeries as reported by Gentry (1981, Figure 4-9), and swim at **40 km/day \pm 10%**.
6. All animals older than 3 years of age are assumed **to** return to **the** Bering Sea. For ages 1-3, the portion returning was calculated by comparing the fraction each age represents in **the** pelagic fur seal data to its fraction of the model population. For yearlings this is 0.7%, for We-year olds it is 22.0%, and for **3-year-olds**, 98.5%.
7. Pregnant females and territorial **males move directly to the** rookeries after passing through **Unimak** Pass. All other seals move randomly among feeding area at sea and their rookeries according to probabilities of being on land. For non-territorial males, the probability of **going to** the rookery is 19.4%, after Gentry (1981). Non-lactating females spend 10% of their time on land.

8. When the **model** is initialized, seals are assigned to rookeries according **to** the distribution of bulls reported 'by **Kozloff** (1985, Table 4-7). Subsequently, seals born on a given rookery **will** continue to return to that rookery.
9. The **portion** of bulls **which** become **territorial** is 72.4% up **to** a maximum number of territories of 12,827 as derived from bull counts. The age distribution of territorial males is **according** to Johnson (1968, Table 4-8).
10. Based on the observed probability distribution of Peterson (1965), territorial males abandon their territories after spending 17 to 77 days on land. Territorial **males** have an equal probability of remaining on their territories for each of **the** 61 possible durations. After abandoning their territories, they subsequently behave as other males.
11. Lactating females **move** on and off the rookeries according to the probability schedule **observed** by Gentry and **Holt** (1985). The duration of visits to land for pupping and nursing are assumed to be as in Figure 4-11. **The first visit (pupping) averages 7.4 days**, and subsequent visits (nursing) average 2.2 days, with the exception of the last **visit** which averages 3.3 days. The duration of a trip to sea is proportional to the age of the pup: $\text{duration} = 0.04(\text{age}) + 4.0 \pm 1.5$ days.
12. Seals are distributed among feeding areas according to an analysis of feeding seal density by one degree longitude and half-degree latitude grids. The feeding-seal density distribution forms a probability distribution of feeding areas, **to which** individual seals are assigned at random (Figure 12a, b, and c). It is assumed that lactating females repeatedly return to a single assigned feeding area. All other seal age/sex types are assumed to randomly select among 5 feeding areas.
13. In **moving** to and from feeding areas, seals are assumed to swim at 4.5 knots an average, which allows **lactating** females ~~to~~ reach the farthest feeding areas and return in accordance with the average schedule observed by Gentry and Holt (1985) and is close to observed swimming speeds of gray seals by Lavigne et al (1982). A random components of plus or minus 10% is induced on both velocity and direction when seals are moving,
14. While feeding at sea, seals move in random directions within the selected feeding area at 20 km/day. Seals are assumed **not** to haul out on **land** at any time **while** feeding at sea.
15. Seals leave the **Bering** Sea according to distributions of last **sightings on** the rookeries of **immature** males **by** Gentry (1981) and of lactating females by Gentry and **Holt** (1985, Figure 4-13). Pups and **non-lactating** adult females **are** assumed **to** leave at the

same time as lactating females. All males and immature female seals other than pups are assumed to leave at the same schedule as the immature males (Figure 4-13). Pups are assumed to swim at 20 km/day \pm 10%, with seals older than 1 year at 40 km/day \pm 10%, while in transit to **Unimak** Pass.

16. Rather than tracking seals individually, seal points representing groups of seals of a given age and **sexual** status are **used**. For migration model simulations without oil spill interaction, 40 replicate points of each seal type were found to be adequate to fit observed distributions (Table 4-9). Thus, seals represented by a single point are assumed to move in unison.

(C) Fur seal model - oil spill model linkages

1. The time step for resolving both oil and fur seal movements is 3 hours. Velocities within a time step are assumed to be constant.
2. Intersections of oil spinets (slicks) and seal points are assumed to oil **all** the seals represented by a seal point, regardless of the time spent in oil.
3. Mortality rates from oiling are varied in different runs at assumed values of 25%, 50%, 75% and 100%. These mortality rates are independent of weathered state of the oil.
4. Although a seal point may remain in oil for **more** than the 3 hour time step or be **re-oiled** a number of times in a given day, the mortality is applied only once daily.
5. Seals which do **not** die when oiled on a given day may be **re-oiled** on subsequent days and may suffer mortality at that time.
6. Oiled seals which do not die are assumed to recover completely. Natural mortality, pregnancy rates, and other behavior are **the** same as for **un-oiled** seals. No avoidance of oil is assumed for future encounters.
7. The number of seal points necessary in runs with simulated oil spills varies inversely with the size of the spill and the density of seals in the spill location at the time of the spill. At least 40 replicate points must be used to adequately distribute the seals (Table 4-9). For the simulated spills reported here, 60 replicate points of each seal type are used (Table 6-5).
8. Spilled oil is represented by discrete circular spinets, within which oil coverage is continuous. It is **assumed that** the inclusion of more complex spinet shapes, or of "patchy" open water areas within a spinet, **and** a resultant **larger** gross

spinnet size, would not significantly alter **the** computed seal-oil interaction rates.

9. Two extreme cases are assumed when oil comes ashore at a rookery.
(1) **All seals** remaining on **the** rookery are assumed not to enter the surf zone and not to be oiled, so that only seals passing through the surf zone are oiled. (2) **All** seals on the rookery are assumed to enter the water at some time during each day, and so are oiled.

(D) Oil Spill Model

1. Spreading is assumed adequately estimated by a simple equation developed by Fay (1971) and modified by Mackay (1980) .
2. **Evaporation** is assumed adequately represented by the methodology of Payne et al (1984), which relies on the mass transfer rate of Mackay and Matsugu (1973).
3. Entrainment is computed according to the algorithm reported by **Spaulding** et al (1982), according to which very little entrainment occurs after the first 4 days of a **spill**.
4. **Advection** is equal to the local surface current velocity plus 3% of the wind speed, with a variable veering angle according to **the** algorithm of **Samuels** et al (1982).

(E) Oil spill scenarios

1. Two spill scenarios were assumed in the study: (1) at 57°N, 171° W near St. Paul Island on July 1, and (2) at 54.9° N, 166.1° W near Unimak Pass on June 25.
2. The amount of oil spilled was 10,000 barrels of Prudhoe Bay crude released in five **equal** amounts ("spinets") over 12 hours at 3 hour **intervals**.
3. Oil spinets coming ashore are assumed to remain in the **nearshore** surf zone.

8.2 **Conclusions**

The percentage of the equilibrium population **which** dies from natural causes each year is 16% for females and 29% for males. For the 1986 population with continued entanglement, mortality due to **natural** causes plus entanglement is 18% of the females and 32% of the males over 1 year. In comparison, the "extreme **case**" spill **simulations herein would be** expected to oil and kill at most about 4% of the population. Since the

number of seals oiled by a given oil simulation is approximately proportional to population size, these percentages would be similar at other population sizes, assuming a similar age and sex structure.

The recovery time of the fur seal population following perturbations due to hypothetical oil spills was of particular interest in this study. We defined recovery time as the time from the initial perturbation until the difference between oil-affected and non-affected populations became less than a specified percentage of the non-affected population size. We have used both 0.1% and 1% as measures of recovery, noting that 1% is near the level of accuracy for pup counts on the rookeries. At the 0.1% level, the recovery time for the maximum oil-affected case is about 70 years; at the 1% level, which more closely reflects our ability to observationally discern population differences, the recovery time is about 25 years for the worst case modeled. For the smallest case simulated here, fewer than 1% of the population was killed.

The work reported here suggests that the effects of a single large (10,000 barrel) oil spill on the Alaskan fur seal population would be imperceptible between 0 and 25 years, depending on the assumed oil-induced mortality rate. Density dependent control appears weak in the northern fur seal population, as is typical of other populations of large marine mammals (Fowler and Smith, 1981). For this reason, the up to 25 year time response for recovery is virtually the same for a population in decline (due to other sources of mortality) as for a population near equilibrium, and is dictated primarily by the reproductive rate and lifespan of female fur seals. In the case of a continuously declining population, additional seal mortalities due to an oil spill result in a decrease of the population somewhat sooner (i.e. perhaps a year to several years) than would otherwise be the case.

Only single spill events have been investigated here, although multiple spills are a possibility. The two 10,000 barrel oil spills simulated here resulted in population reductions of at most 4% for the year of the spill, but these spill scenarios were selected to occur at times and places when the fur seals are most vulnerable. The probability of occurrence of such an event is less than 0.02; the probability of two such events is therefore less than 0.0004, assuming independence between events. These probabilities could be significantly decreased by controlling exploration, production, and transportation activities to avoid vulnerable times and places, such as the Pribilof Islands in July and August, and Unimak Pass in April and November.

In order to more accurately project population responses to perturbations such as might be associated with an oil spill, more quantitative information on density dependent mortality relationships for all ages of seals is required, and particularly for female juveniles and pups. The recovery and stability of any population depends on density-dependent changes in reproduction or mortality. Reproductive rates and litter sizes for large mammal populations appear relatively constant (Fowler and Smith, 1981). If a constant additional mortality

rate, such as that due to entanglement, is balanced by increased survival rates at a lower population density, the population will maintain itself at that lower density, but will not be able to recover to the former higher numbers until **the** additional cause of mortality is removed. **The** model results presented here suggest that the population of the 1950's suffered lower mortality rates than the estimates based only on recent data (i.e. those of Lander, 1980). The analysis of Section 4.1 showed that even the lowest pup and juvenile mortality rates of the range seen over all years are too high to allow the population to reach 2 million individuals if female and male juveniles are assumed to die **at** equivalent rates. Therefore, female juvenile survival must **be** higher than that for males, at higher population sizes at least, or perhaps natural mortality has changed over the years due to environmental changes. Analysis of mortality using data over small ranges of years, and specific population sizes may shed more light on this subject. Quantitative age-specific estimates of exogenous causes of mortality, such as entanglement, are also needed.

The population dynamics model developed here may **be** applied to other problems concerning fur seal population dynamics, such as investigation of the decline in the **Pribilof** Island population between 1958 and the present. As better estimates of entanglement mortality rates become available, the **model** may be used to test whether lethal entanglement can account for the recent decline, and how much of the decline still remains unexplained. Also the significance of recent upturns in **number of pups** born and, presumably, population size (Table 4-4; C.W. Fowler, S. Zimmerman, personal communication) may be investigated. The effect of the female to male juvenile survival ratio, or other more explicit estimations of female juvenile survival rate (when data becomes available), on recovery rate from perturbations induced by **oil** spills or other causes remains unexplored. Preliminary analysis (Section 6) shows that the population **model** is quite sensitive to variation in female juvenile survival.

It would be desirable to conduct further sensitivity analyses on the fur seal migration - oil spill interaction component of the model. The number of seals oiled will certainly vary with oil spill size, **location**, time of year, and length of time oil is released. Runs of the model varying spill size, location, and timing to obtain number of seals oiled could be combined with probabilities of spill events to generate a relationship as **conceptualized in** Figure 1 (Executive **Summary**). Number of seals oiled may also vary with such variables as number of discrete spinets used to simulate the release, patchiness within an oil slick, shape of the slick, swimming velocity of seals, and number of feeding areas an individual may visit on feeding forays. Incorporation of the coastal zone oil spill **model now** under development for **MMS** (Gundlach et al, 1986), to simulate oil behavior when a slick approaches a shoreline, would improve simulations such as the St. Paul spill simulated herein.

Finally, the fur seal migration model, **in** conjunction with estimates of population size and structure or the population dynamics **model**, may be

used to estimate fur seal densities in time and space throughout the Bering Sea. Since fur seal sighting data is incomplete and expensive to obtain, this method would be advantageous in a number of applications.

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APPENDIX

Summary **Tables** of Literature Sources
for Parameters, and Reviews of Previous
Pinniped Population Models

Table A.1 Descriptions and literature references for parameters evaluated for conceptual model. Only articles containing recent information appropriate to the conceptual model are included. References are to northern fur seals unless otherwise specified. We have not referenced the population data in the annual reports of fur seal investigations issued by the National Marine Mammal Laboratory. The population data provided in these reports is compiled and analyzed in the later reports and publications summarized below.

Parameter	Reference	Description/Value
<u>Broad summaries of data sets</u>		
Lander 1980b		Summary of all land data collected by US and USSR through 1979
Lander 1980c		Summary of eastern Pacific pelagic data of the US and Canada
Lander and Kajimura 1980		Summary of Western Pacific pelagic Data of the USSR and Japan
Scheffer et al. 1984		History of scientific study and management of the Alaskan fur seal
N Pacific Fur Seal Corn, 1984 1977-80		Summarizes fur seal research by US, USSR, Canada, and Japan,
N Pacific Fur Seal Corn. 1980		As above for 1973-76
<u>Metabolic rate</u>		
Kooyman et al. 1976		Immersed V02 rates 20-31, varies by activity, oiling incr. 50%
Miller 1978		Determines oxygen intake in fur seals, pelagic requirement = 197 kcal/kg per day
Blix et al. 1979		Metabolic rate of fur seal pups: 3.5 W/kg when dry 18 W/kg wet & cold

Growth and other physiological factors

Bigg et al. 1977	Timing and duration of molt in captive fur seals
Scheffer and Johnson 1963	Molt in the northern fur seal
Lander 1979	Size and growth of fur seals from pelagic data
Bigg 1979b	Evidence for lower growth in 5-11 r. clds in recent years
Lander 1980a , 1981	Summarizes data on biomass
Scheffer and Wilke 1953	Examines growth in fur seals
Hartley 1982	Finds evidence of greater length and tooth wt. in recent years

Population size and structure

Lander 1980a, 1981	Provides new life table of fur seals using most recent data
Smith and Polacheck 1981	Critical examination of fur seal eal table for periods of no growth
Kenyon et al , 1954	Study of population and components of herd through 1951
Johnson 1975	Summarizes northern fur seal pups born through 1970, Pribilof fur seal population estimated at 1.2 mil in 1970
N Pacific Fur Seal Comm 1984	Most recent pup production and population estimates

Reproduction

Lander 1980a , 1981	Summarizes reproductive data from
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	pelagic collections in life table
York 1983	Examines age at first reproduction in northern fur seals
York 1979	Reproductive data by area, month, and year from 1950-74 data
York 1980a	Examines pregnancy rates in relation to <i>location</i> and migration
York 1980b	Changes in age at first reproduction by year
Smith and Polacheck 1981	Provide new calculation of pregnancy rates for 1958-61, stable population
Bigg 1979a	Pregnancy rates (age >6) by region, and month. Decline in recent years
Harwood and Prime 1978	Do not find density dependence in British grey seals
Chapman 1964	Summarizes data on pregnancy rates
Chapman and Johnson 1968	Reports on development of new method for determining pup born
Spotte and Adams 1981a	Reproduction in captive fur seals
Bigg 1984	Evidence for fur seals being able to control timing of parturition
Gentry and Goebel 1982	Eastous limited to narrow time, juv. males (45 kg) are fertile

Mortality

Lander 1980a, 1981	Survival data is summarized from pelagic and land data
Harwood and Prime 1978	Find density dependent relationship in survival of British gray seal pups
Bonner 1975	Linear density dependent mortality in grey seal pups

Chapman 1964	Calculates female survival by year <i>class</i>
Chapman 1961	Reports higher survival to age 3 at a reduced population
York and Hartley 1981	Calculate mortality from female harvest accounts for 70 population decline
Eberhardt and Siniff 1977	Mortality through juvenile stages most critical density dependent factor
Smith and Polacheck 1981	Survival estimates of female fur seals difficult to support, density dependent survival to age 3 not found in data
Fowler 1981	Density dependent rates in large mammals occur primarily at high populations
Swartzman 1984	Positive correlation between pup mortality and # born
Keyes 1965	Causes of death and pathology of fur seals
Johnson 1968	Mortality of adult males estimated at .38
<i>Gentry</i> and Johnson 1981	Examines predation of sea lions on fur seal pups off the Pribilofs
Keyes et al. 1979	Causes of death of neonates on St. George 1977-1979
Lander 1975	Method of determining natural Mortality
Lyons and Keyes 1984	Hookworm larvae are viable in tissues for several years

Behavior

Kenyon 1960	Reports arrival and departure times adult male fur seals
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Peterson 1968	Summarizes behavior of fur seals on the Pribilof Is.
Gentry 1981	Examines land-sea movements of sub-Adult male fur seals
Bartholomew 1959	Behavior of fur seal mothers and pups
Bartholomew and Heel 1953	General reproductive behavior of northern fur seals
Gentry et al. 1979	Changes in territory size of males and changes in mother/pup ratio on St. George
Gentry et al. 1977	No measurable increase in length of feeding cycles in last 12 years
Gentry and Johnson 1976	Subadult males feeding cycles from radiotagged animals
Gentry and Johnson 1976	Temporal changes in female feeding cycles
Macy 1982	Mother-pup interactions

Distribution and migration

Wilke and Kenyon 1954	General summary of the distribution and migration of fur seals
Kenyon and Wilke 1953	Summarizes data on migration of fur seals gathered in previous 10 years
Kajimura 1979	Distribution of pup/yearlings by month using pelagic and stranding data
Bigg 1982	From historical and pelagic records derives seasonal age-sex distribution in 1 deg lat by 2 deg long
Kajimura 1980	Distribution including some opportunistic sightings and 1 deg long and lat

Gribben 1979

Interchange of subadult males
between St. Paul and St. George

Entanglement

Shaughnessy 1980

Entanglement rates of Cape
ful seals

Fowler 1982

Concludes that entanglement in
debris may be cause of fur seal
decline

Swartzman 1984

Models different hypotheses for
entanglement of fur seals

Feldkamp 1983

Power output of sea lions
entangled in nets is 4-5 times
above normal

Scordino et al. 1984

Reports of fur seal
entanglement on St. Paul Is.

Diet

Kajimura 1984

Opportunistic feeding of the
northern fur seal

Perez 1979

Preliminary analysis of food
from pelagic collections by month
and area

Bigg et al. 1977

Reports food requirements of
captive fur seals

Bigg et al. 1978

Examines annual body weight
variation in captive fur seals

Taylor et al. 1955

Analysis of food habits of fur
seals collected in 1952

McAlister and Perez 1976

Estimates fur seal
consumption by location and season
and type

Sanger 1974

Estimates fur seal food
consumption by age and sex

Wilke and Kenyon 1954

General summary of northern

	fur seal food habits by location
Fowler 1982	Finds no supporting evidence for commercial fish harvests causing fur seal decline
Swartzman and Haar 1983	Commercial fishing in Bering Sea shouldn't have negative effect on seals
Lowry 1984	Considerations for interactions between fur seals and fisheries
Spotte and Adams 1981b	Determines feeding rate as % of weight based on captive females
Lowry et al. 1982	Rank order of food importance by season and region, from unpublished sources
Perez and Mooney 1984	Compares feeding rates of lactating and non-lactating seals.
<u>Oil effects</u>	
Kooyman et al. 1976	Oiling raises metabolic rate approximately 50%
Kooyman et al. 1976	Oiling increase pelt thermal conductance 1.7 to 2 times
Geraci and Smith 1976	Oil effects on captive ringed seal
Le Boeuf 1971	No effect found on wild elephant seals
Brownell and Le Bouef 1971	Search for mortality of elephant seals from an oil spill
Davis and Anderson 1976	Oil effects on wild grey seals
Duguy and Babin 1975	Poisoning of common seal in the wild from oil ingestion
Geraci and Smith 1977	Skeptical of toxicity to pinnipeds from direct ingestion

Risebrough 1976

Review of limited information of
hydrocarbon uptake in marine
mammals

Smith et al. 1983

Bottlenose dolphins **avoid oil**
coming into contact with it

Geraci et al. 1983

Bottlenose dolphins able to
detect thicker films of oil

Table A.2. Summary Table of **Pinniped** Population Models

Model Reference: Allen, 1975

Purpose: Management of the Northwest Atlantic harp seal population

Description: This is a female-based Leslie matrix life table model, operating on 30 year classes. Considerations by year class include births, hunting mortality, and natural (other) mortality. Flow charts of the model are given in **Capstick** and Ronald, 1982.

Validation and Testing: Model sensitivity evaluated relative to survival and pregnancy rates and population size.

Application and Findings: For short duration (< 5-10 year) projections, the model is relatively insensitive to survival and pregnancy rate estimates. Population size, on the other hand, proved important for projections of both numbers and ratios of numbers by year class. Because the model is linear, and the dominant **eigenvalue** exceeds unity, the model is unstable for long term projections.

Limitations: Leslie model as applied is limited to a one year timestep. Seasonal or spatial considerations are problematic to include with this approach.

Model Reference: **Bulgakova**, 1971

Purpose: Estimation of optimal sustainable yield from Robben Island fur **sealherd**

Description: Comparison of three stock-recruit models based on work by Chapman (1961)

Validation and Testing: None

Applications and Findings: Recommended levels of kill were similar for all three models.

Limitations : Recruitment is assumed controlled by pup density dependent factors only. Estimates of many herd parameters were "very rough or almost arbitrary", so that results are highly tentative.

Model References: **Capstick** et al. 1976

Purpose: Comparison of various **model** assumptions for effects on pup production and sustainable yield forecasts.

Description: Four variations of the model by Allen (1975) were investigated **in** comparison to the original linear version. These variations were

- (1) an exponential density dependent change in average age at maturity,
- (2) a linear version of maturation rate,
- (3) a variable pregnancy rate, and
- (4) changes in the sex **rates**.

Validation and Testing: Model estimates of pup production were compared with field estimates,

Applications and Findings: **All** model versions overestimated pup production.

Limitation: Study confirmed that model output is **very** sensitive to input parameters and assumptions.

Model Reference: **Capstick** and Ronald, 1982

Purpose: Improved documentation for and incorporation of density dependent birth rates by age class in the **Allen** (1975) model.

Description: The Allen (1975) Leslie matrix model **was** modified to include a density dependent female maturation **ogive**, with mean maturation age increasing with herd size. Both minimum pupping age and maximum pupping rates can be input by the user.

Validation and Testing: None applied, but authors **suggest** **hindcasting** as a possible test.

Application and Findings: Model forecasts of herd size under specified constant hunting pressure are more optimistic under **the** density dependent feature than when this feature is omitted. Thus neglecting density dependence is a more conservative approach to herd management.

Limitations: **Leslie** Matrix approach as applied is limited to a one

year timestep.

Model Reference: Chapman, 1961

Purpose: Development of model for Alaska fur seal parent-progeny relationship.

Description: Model assumes that weight gain of pups is proportional to food intake of lactating females (compensated for energy requirements), that the feeding area is proportional to population size, and that survival probability is proportional to food intake.

Validation and Testing Procedures: None

Application and Findings: Two equations are **investigated** for the relationship between pup population **and** survival to age three. One equation is a logistic form, while **the** second is developed specifically for the fur seals. Both equations are dome-shaped.

Limitations: Chapman (1973) **notes** that assumed shape of stock-recruit curve is not supported by **observed** fur seal population dynamics.

Model Reference: Chapman, 1973

Purpose: Review and exploration of models for estimation of maximum sustainable harvest,

Description: Four simple parametric density **dependent** "spawn-recruit" equations are investigated in relation **to** fish as well as the Alaska fur seal population. For fur seals, a catch equation is formulated allowing for recruitment of males and females, rates of replacement of males and females from recruitment, and the **number** of adult females per adult male.

Validation and Testing: None

Application and Findings: The **adult** female population necessary to achieve MSY is estimated at 471,000.

Limitations: The author points out that the accuracy and constancy of parameters in the catch equation are uncertain factors requiring further

exploration.

Model Reference: DeMaster, 1981

Purpose: Incorporation of density dependence and harvest into a **Leslie** Matrix model for **Weddell** seals,

Description: The model is based on a projection matrix with 25 age classes, with minimum **pupping age** at 4 years. Age specific **survival** is computed according to one of 4 density **dependent** functions. These hypothesized functions include both linear and non-linear forms.

Validation and Testing: None

Application and Findings: Because of the hypothetical nature of the density dependent functions, generalization of results is difficult. The author concurs with the general expectation that population regulatory mechanisms **will** be variable from one species to the next, and that a general model for maximum sustainable yield is not achievable.

Limitations: In addition to the time domain limitations imposed by the discrete matrix formulation, the work **focusses** on a qualitative comparison of population projections under hypothetical assumptions.

Model Reference: Eberhardt and **Siniff**, 1977

Purpose: To evaluate criteria for determining **Pribilof** fur seal maximum sustainable yield.

Description: A three-equation, female based model is used, with three survival rates: from birth to age 1, age 1 to 2, and constant thereafter. Reproductive schedules and survival rates are estimated from various literature sources. The **model** follows an application by Leslie (1966) to a guillemot population.

Validation and Testing: None

Applications and Findings: The authors suggest that age at first reproduction may not be very important as a compensatory or regulatory mechanism, due to the natural longevity of seals. Survival through immature stages is proposed **as the** factor of major importance in determining population dynamic behavior. **The** tentative conclusion is drawn that maximum sustainable yield may be greater than a median value, so that the optimal population level may be close to the

environmental carrying capacity.

Limitations: Conclusions are necessarily tentative, since **survival** through immature stages and density **dependent** factors are poorly known. It is pointed out that herd management at or near the carrying capacity is a conservative policy **in terms** of species survival.

Model Reference: Eberhardt, 1981

Purpose: To explore population data for the **Pribilof** fur seals, estimate key parameters, how these vary with population density, **and** deduce an optimum strategy for management.

Description: As in **Eberhardt** and Siniff (1977), the **Lotka** equations are used in their summation (rather than integral) form, with associated rates derived from various **data** sources, A stochastic capability is introduced in both **survival** and reproductive success rates, A function for density dependent juvenile **survival** is incorporated, with **parameters** fit by least squares **to** estimates of pup **survival**.

Validation and Testing: Graphical comparison of modeled versus field-estimated numbers of female pups born each year, 1952-1977,

Applications and Findings: Applied to test hypothesis that the drop in fur seal pup production beginning **in** 1966 could be accounted for **by** a reduction in pup survival, **combined** with the female harvests of 1956 to 1968. It is suggested that the **observed** decline in population **level** up into the 1970s may indeed be the result of these processes.

Limitations: Uncertainties noted by the author include the estimation of adult and pup **survival** rates and pup production. The explanation for the downward population trend does not account for the continuation of this trend in recent years.

Model Reference: **Flipse** and **Vellig**, 1984

Purpose: Analysis of population stability of the hooded seal population near Jan **Mayen** Island in the NE Atlantic.

Description: A Leslie matrix model is used. Age specific reproductive rates are taken from the literature. Natural survival rates are estimated from the catch curve. Hunting effects are included through an iterative solution technique.

Validation and Testing Procedures: None

Application and Findings: Three assumptions are made regarding the initial size of the female breeding population, and the eigenvalue of the transition matrix is calculated. The results indicate that, up to 1975, hunting pressure was very near the maximum level sustainable by the population. Continued decline in the population size, and incomplete understanding of population dynamics, are cited as arguments in support of a restrictive management policy.

Limitations: The major source of uncertainty in the study appears to be the size of the breeding population of females (age 4 and older),

Model Reference: Frisman et al. 1982

Purpose: Study population dynamics of northern fur seal herd on Tyuleniy Island (NE Pacific)

Description: Model includes 16 age and sex groups: 9 female age groups (3 to 11 years), 5 bachelor male age groups (2 to 6 years), bulls older than 6 years, and pups. Only males are subject to harvest. Density dependent survival of pups is modeled according to a linear function of pup density.

Validation and Testing: Graphical comparison of modeled and observed pup, female, and bull seal population levels, 1966-1978.

Application and Findings: Model hindcasts of male and female fur seal population dynamics are made. Survival of young females appears considerably more sensitive to population density than survival of young males, although the data reflects considerable scatter. A pregnancy rate based on mean harem size (ratio of mature females to bulls) is estimated from data.

Limitation: The authors note that the model is very sensitive to density dependent survival and the age structure of the female population, and that further work is needed in this regard.

Model Reference: Harwood, 1981

Purpose: Examination of alternate management strategies for the British population of gray seals.

Description: **Eigenvalue** analysis of a Leslie matrix is pursued to evaluate population stability. The matrix incorporates 7 age groups, with density dependent survival at the pup and the two eldest levels.

Validation and Testing: None

Application and Findings: Several hypothetical management strategies are compared, with focus primarily on economically attractive pup harvests. Model results show that taking a fraction of the annual pup production is less destabilizing than taking a fixed quota of pups each year.

Limitations: The **form** and coefficients for density dependent pup survival are probably the major source of uncertainty.

Model Reference: Lett and **Benjaminson**, 1977

Purpose: To supply advice on NW Atlantic harp seal quotas, and an estimate of the maximum sustainable yield.

Description: The **model** incorporates 25 age classes, divided into male and female groups. Hunting and natural mortalities are included. Fertility and maturation are population size dependent.. Pup mortality in the model is not density dependent. Natural **mortality** and harvest mortality rates at all ages are subject to stochastic variability, reflecting uncertainty in parameters due both to sampling error and environmental variability.

Validation and Testing: Comparison of projected and observed population structures.

Application and Findings: Given the parameters of the **model**, the equilibrium population size was estimated at 3.7 million seals. Maximum catch levels for pups and adults were suggested.

Limitations: The work demonstrates the rate of growth of **uncertainty** bounds as population levels are projected into the future. The authors suggest that quotas not be set **more** than 3-5 years in advance, and the complete reevaluation of the population dynamics be undertaken every 5 years.

Model Reference: Lett et al. 1981

Purpose: To study **density** dependent processes **in** the NW Atlantic harp seal population.

Description: The model of **Lett** and **Benjaminsen** (1977) is updated to include density dependence in pup survival. Although the relationship is supported **by** data, reasons for the dependence are not clear in the case of the harp seal.

Validation and Testing: None additional.

Application and Finding: Maximum population sizes (4.1 to 5.5 million seals) **and** production **curves** ~~w~~e re estimated under various density dependent assumptions. Maximum sustainable yield is estimated at about 200,000 animals, for a population size of **1** to 2 million animals. A critical minimal stock size of 800,000 is estimated,

Limitations: Factors contributing to the overall **model** variance include uncertainties associated **with** natural mortalities, the uncontrolled aboriginal hunt *in the Arctic*, and the hunt by **landsmen** in Newfoundland and Quebec.

Model Reference: Nagasaki, 1981

Purpose: Population dynamics analysis and optimal yield estimation for the northern fur seal, including **Pribilof** and Commander Island herds.

Description: **Ricker** and Beverton-Holt stock recruit models are investigated, along with a logistic curve for pup production.

Validation and Testing: Comparison between modeled and actual catch for years 1920-1958. .

Application and Findings: Recommended kills of furs **seals** on the **Pribilofs** are around 55,000 males aged three, and about 13,000 females.

Limitations: Findings based on assumed density dependence operating through **unknown mechanisms**. Recommendation of female kills may have contributed to subsequent population decline.

Model Reference: **Shaughnessy** and Best, 1982

Purpose: To determine annual **yield** of yearlings and mature . female abundance for South African fur seals at population equilibrium.

Description: Assuming a stable initial population size, and representing only females, the population size is projected under several different sealing rates. Annual survival rates **are** density indendent. Both pregnancy rate and pup **survival** rate are density dependent, based on **Pribilof** fur seal data.

Validation and Testing: Sensitivity analysis on model parameters.

Application and Findings: Mode 1 runs suggest that the maximum sustained harvest rate for young immature seals is about 30% of those pups **surviving** to 8 months of age.

Limitations: **The** model was found to be very sensitive to pregnancy and pup survival rates. Mortality rate of adult females is poorly known for this population, but is a third important parameter in determining maximum sustainable harvest.

Model Reference: **Siniff** et al., 1977

Purpose: Analysis of **Weddell** seal population dynamics.

Description: This female-based model allocates new recruits to the breeding population in proportion to the available space in a given colony. Both adult mortality and allocation of new recruits to available space are stochastic processes.

Validation and Testing: Comparison of modeled with observed dynamics.

Application and Findings: Model runs showed that previously reported reproductive and **sruvival** rates were inconsistent, given the observed mean population size. The model also indicated the existence of a surplus of adult females, which was later confirmed by field observations.

Limitations: Pup survival rates through the first year of life is probably the primary **mechanism** for population regulation, and is also the parameter about which least is known.

Model Reference: Smith and Polacheck, 1980

Purpose: Investigation of effects of age structure and density dependence on results of harvesting females.

Description: Leslie matrix of female population component. Density dependent factors are incorporated for both fecundity and survival matrix elements.

Validation and Testing: Comparison of modeled and predicted numbers of pups born over time.

Application and Findings: Results suggest that observed population dynamics cannot be explained by a simple self-regulation model.

Limitation: Density dependent factors are essentially hypothetical.

Model Reference: Swartzman, Harr, and Sullivan, 1982

Purpose: Investigation of potential carrying capacity reduction due to commercial fishery harvest of species such as pollock and herring, mainstay food resources for fur seals.

Descriptions: The model considers the possible energetic effects on lactating seals on the Pribilof Island due to reduction in food or to changes in seal abundance. The model focuses primarily on female seals during their period of residence in the eastern Bering Sea. The seals are separated into lactating and non-lactating seals by age class. Computations are made for average seal weights and populations at age as they are influenced by temperature, food availability of five groups of prey, and seal respiratory and growth demand. Seal arrivals and pupping and weaning cycles are expressed as monthly averages of seal abundance. Prey respond to seal predation as well as to natural and fishing mortality, and are annually increased by recruitment which is read in as a model driving variable. There is no predation considered on the prey other than seal predation. Other predation sources are included as 'natural' mortality. Prey abundance is included as a month-specific availability factor for each prey type. All seal age classes are assumed to have the same diet and reproductive pattern. The only differences between age classes (from age 3 to age 13+) is the fraction of mature and fecund females and the average weight, which affects the maximum ration and respiratory demand (Swartzman, 1984b).

Validation or Testing Procedures: Subjective comparison was made between **modeled** and observed growth patterns over the summer pupping period.

Application and Findings: Applied to examination of energetic implications of increased seal abundance, reduced prey abundance, and reduced prey availability (**Swartzman** 1984). Implications are that" fur seals are not greatly affected **when** prey abundances or availabilities are reduced within plausible ranges, the measure of impact being estimated percentage loss in annual milk per pup after 6 years of altered conditions.

Limitations: Prey abundances, the half saturation constant for density dependent feeding rate, prey availability are all relatively uncertain parameters. Changes in respiration and feeding rates **with** temperature are also uncertain.

Model Reference: **Swartzman**, 1984a

Purpose: Investigation of entanglement and altered **harvest** strategies on status and future of Bering Sea fur seal population.

Description: Basically a **Beverton-Holt** age class, female-based, density dependent pup **survival** model.

Validation or Testing Procedures: Sensitivity analysis on pup survival density dependent parameters.

Applications and Findings: The model was applied to a variety of assumed levels of entanglement, but failed to come to equilibrium **when** all age classes were subject to entanglement and survival time was less than 12 **months**. This is apparently a mathematical **anomaly** within the model, rather than a fur seal population dynamics fact. The model demonstrates that entanglement could be a significant contributing factor to the observed fur seal population decline. The model also suggests that termination of the fur seal **harvest would** do little to increase the future population abundance.

Limitations: This model, and both Beverton Holt and **Ricker-type** models in general, are highly sensitive to density dependent parameters, about which little is known.

Model Reference: **Trites**, 1984

Purpose: Assessment of current status of **Pribilof** Islands fur seal herd.

Description: Single species male and female age structured model without density dependent mechanisms. Juvenile survival rates are allowed **to** vary.

Validation and Testing: Validation performed through sensitivity analysis.

Application and Findings: Study suggests that observed population decline **is** the result of harvesting females and **a series** of low **juvenile survival rates**.

Limitations: Model" is extremely sensitive to adult survival estimates.